Università degli Studi di Napoli “Federico II”
Dipartimento di Ingegneria Industriale
Scuola di dottorato in Ingegneria dei Sistemi Meccanici
XXVII ciclo

Systematic innovation

Tools and methods supporting the concept design process

RESEARCH DOCTORATE THESIS

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March 2015

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ideas
CREATE

ἢ τὰν ἢ έπὶ τᾶς
«Either [with] it [your shield], or on it»

- *[Plutarch, Moralia, 241]*

Preface

Personal notes

This thesis is the result of a three years' work which covered many methodological aspects and case studies in order to find viable methodological instruments supporting the concept design process in each of its aspects. It also involved the contribution of several research teams of different institutions.

The results achieved could not have been accomplished without the indispensable assistance provided by my academic tutor, Prof. Giuseppe Di Gironimo, who guided me through the entire doctorate. He represented for me a constant support to confront with, in order to take the correct choices. Above all, he gave me the fundamental opportunity to grow as an engineer and as a scientist.

I would also thank all the other people who worked with me, in particular Jarmo Alanen, Alessio Balsamo, Dario Carfora, Domenico Marzullo, Kenan Melemez, Fabio Peluso, Rocco Mozzillo, Fabrizio Renno, Andrea Tarallo and Risto Tuominen, for their technical support and their valuable contribution, which covered every aspect of my research. I am also grateful to Prof. Antonio Lanzotti and Prof. Timo Määttä: they shared with me valuable advices, which improved the quality of my scientific production.

Acknowledgements

The present work was developed within the framework of the project "Dottorato in Azienda" of Italian "Regione Campania". The work was mainly carried out in collaboration with the CREATE Consortium. Part of the research activities were carried out in collaboration with the teams working on the projects "Digital Pattern product development" of the Italian Ministry of Education, University and Research (MIUR) and "INSIST" of the Italian "Regione Campania".

The activities related to fusion engineering were carried out via the collaboration of the "Divertor Test Platform 2" (DTP-2) team, in charge of ITER divertor RH tests, and located in VTT's Labs of Tampere (Finland), the Italian national agency for new technologies, energy and sustainable economic development (ENEA), and the IDEAinVR team of CREATE Consortium, with competence in interactive design and VR simulations and located in the Virtual Reality Lab of University of

Naples Federico II (Italy). These studies were supported by the European Community under the contract of the association between EUROfusion and ENEA/CREATE, within the framework of the European Fusion Agreement.

The studies related to forest engineering were developed with the contribution of the Scientific and Technological Research Council of Turkey (TÜBİTAK), the Forest Engineering Department of the Bartın University (Turkey), and the Italian National Research Council – Institute for the Appreciation of Wood and Arboreal Species (CNR – IVALSA).

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Abbreviations

AD	Axiomatic Design
AHP	Analytic Hierarchy Process
APDL	Axiomatic Product Development Lifecycle
CI	Consistency Index
CMM	Cassette Multi-functional Mover
CR	Consistency Ratio
DEMO	DEMonstration fusion power plant
DES	Discrete Event Analysis
DMU	Digital Mock-Up
FAST	Fusion Advanced Studies Torus
FBS	Functional Breakdown Structure
FMECA	Failure Mode, Effects, and Criticality Analysis
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
LBA	Low Back Analysis
LS	Locking System
MCDA	Multi Criteria Decision Analysis
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OWAS	Ovako Working Posture Analysis
PBS	Product Breakdown Structure
PDL	Product Development Lifecycle
PEI	Posture Evaluation Index
QFD	Quality Function Deployment
RAMI	Reliability, Availability, Maintainability and Inspectability
RH	Remote Handling
RI	Random Index
RULA	Rapid Upper Limb Assessment
SCEE	Second Cassette End-Effector
SMH	Scheduled Machine Hours
SRD	System Requirements Document
TRIZ	Teoriya Resheniya Izobretatelskikh Zadatch (Russian for *“Theory of Inventive Problem Solving”*)

Abstract

Concept design is a complex and iterative process in which design tasks are highly interdependent. Such process should reflect the specific design requirements, objectives and constraints applicable to the product. However, while design freedom is at its maximum in early design stage, product knowledge is only partially known initially and is changing over time. The aim of this work was the integration of methods to improve three areas belonging to the concept design stage. The first is the effective determination of requirements at the beginning of a project, given that all subsequent steps are dependent upon the completeness, accuracy and specificity of these requirements. Early requirements should be translated effectively into technical characteristics. The second is the systematically generation of innovative concept features that should be able to solve design contradictions. The third is the support of the selection of the most feasible solutions based on multi-criteria decision making techniques, relying on tools such as concept evaluation in a virtual environment, and process simulation software.

We worked on six different case studies related to two very different subjects: fusion engineering and forest harvesting. The distance between the topics helped to prove the general efficacy of the methodological instruments considered in this work. The use of quality function deployment, as well as the axiomatic design approach, proved to be a viable systematic way to achieve solutions in complex design situations, limiting the risks arising from the lack of requirements. In this context, TRIZ provided the valuable contribution to overcome technical issues found in previous design phases. The simultaneous comparison of product alternatives in an immersive virtual reality environment, together with the use of the analytic hierarchy process, has speeded up the concept review process. The use of stochastic models in discrete event simulations allowed comparing product concepts in terms of the impact on the process in which they need to be integrated.

1 Aims and motivations

Managing product development process is a complex and challenging task, especially when talking of new product development. Management practices and tools are successfully applied to other process types, but they seem to lack support in the context of new products development processes. The management of this kind of processes is more challenging than other processes because the requirements are continuously changing and the process is inherently iterative, and unique. Product knowledge context, incorporating information about the product, requirements, technology and other factors, dynamically evolves during the entire process. The increasing knowledge about the product, while designing, manifests in design changes of previously accomplished activities. The need to rework the design of one product component influences changes in other components. The iterative nature of the process is considered a major source of increased product development lead-time and cost; thus, systematic tools for concept generation and simulation are essential. Moreover, designers should be provided with decision-making methods to select alternatives when needed. Formal methods are required for modelling the dynamic process structures.

Product development processes are highly complex, dynamic, iterative, and unique (Karniel & Reich, 2011). They are complex because they involve multiple disciplines contributing to the development of complex multidisciplinary products (e.g., mechatronics), that have limited resources, shortened development time and increased quality and regulatory demands. In particular, those processes are inherently iterative due to the interdependencies between the design activities. The design process reflects the specific design requirements, objectives, and constraints applicable to the product. The development process of new products presents additional complexities as the knowledge required for planning the process is only partially known initially (Reich, 2008; Smith & Morrow, 1999), and is changing during the time (Eppinger & Ulrich, 2011). Figure 1 depicts the product knowledge and design freedom as a function of time (Ullman, 2003). It also shows the quality determined and cost incurred as a function of time. From the quality determined graph, it is clear that the most important time is the beginning of the project where knowledge is scarce. This paradoxical situation inevitably leads to changes in the product and the process. Consequently, we cannot hope to

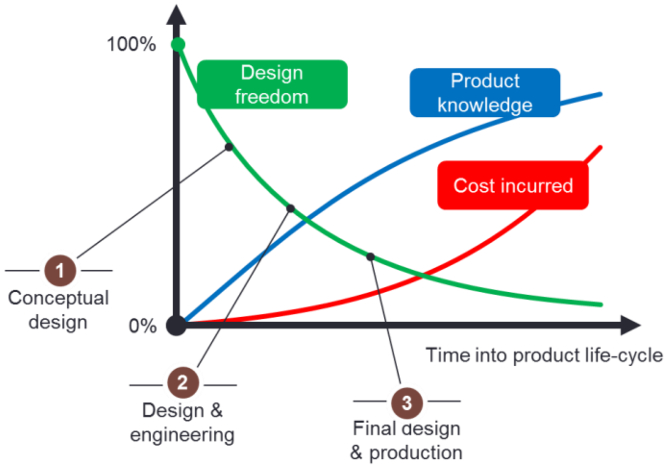

Figure 1. Product knowledge and design freedom against time

define the scope of work needed for a new product, nor we could plan how to manage it a-priori. Hence, the planning should be repeatedly updated during the process, incorporating the additional product knowledge (new activities, or new relations) that is gained. Moreover, due to diminishing design degrees of freedom, the design process will involve iterations to redo previously accomplished design activities.

1.1 The importance of requirements' collection

The traditional practice of Systems Engineering Management involves the determination of requirements at or near the beginning of a system development project. All subsequent steps are dependent upon the completeness, accuracy and specificity of these requirements. Within the context of 15288 ISO/IEC (2008), requirements are specifically mentioned in two of the technical processes and are drivers for many of the system life cycle processes. Depending on the system development model, requirements capture may be done nominally once near the beginning of the development cycle or, as for agile methods, be a continuous activity. When applying systems engineering, there is near unanimous agreement that successful projects depend on meeting the needs and requirements of the customers. Without establishing detailed requirements, the risk of project failure would be unacceptably high.

When we want to generate flexible solutions, adaptable to a wide set of circumstances, the importance of requirements collection is critical. Requirements engineering is a decision-centric process (Aurum & Wohlin, 2003; Svensson et al., 2011), and decision support plays an important role in enabling the delivery of value to stakeholders (Ruhe, 2005). Hence, decision support is crucial in achieving value to stakeholders. This is further aggravated in market–driven incremental development, where the situation is even more complex (Aurum & Wohlin, 2005), due to that the flow of requirements is not limited to one project, and the requirements are generated from internal (e.g., engineers) and external (e.g., customers) sources (Gorschek & Wohlin, 2006). To deliver business value, a key issue is to decide what to develop; therefore, it is important to make trade-offs between different requirements and stakeholders.

Requirements prioritization is an important part in requirements negotiation and release planning (Ruhe, 2005). Requirement elicitation is an iterative activity and benefits from continuous communication and validation with the customer. No design can be completed before establishment of a system requirement documents (SRD) reflecting all relevant design inputs. Prior to proceed with the physical implementation, a complete, unambiguous, consistent, understandable, traceable and modifiable set of requirements is needed (Haskins, Forsberg, Krueger, Walden, & Hamelin, 2006). Concept design begins from concepts generation based on defined requirements. In complex contests, with a number of stakeholders involved, requirements are not static and one reason for that is the continuous learning and better understanding of the design concept and its environment during design process. During the initial stages it may not be needed to establish all requirements; however, the necessary design criteria should be fixed before starting the related level of design.

Many types of systems have proven to be resistant to requirements determination in concept design stage. As a consequence, application of the traditional management process does not adequately assure operational effectiveness (Willoughby, 1989). Moreover, constant changes occur to the systems during the early phase of conceptual stage, corresponding to the iteration cycles shown in the V-model (Figure 2). In complex systems during this phase the results from parallel tasks,

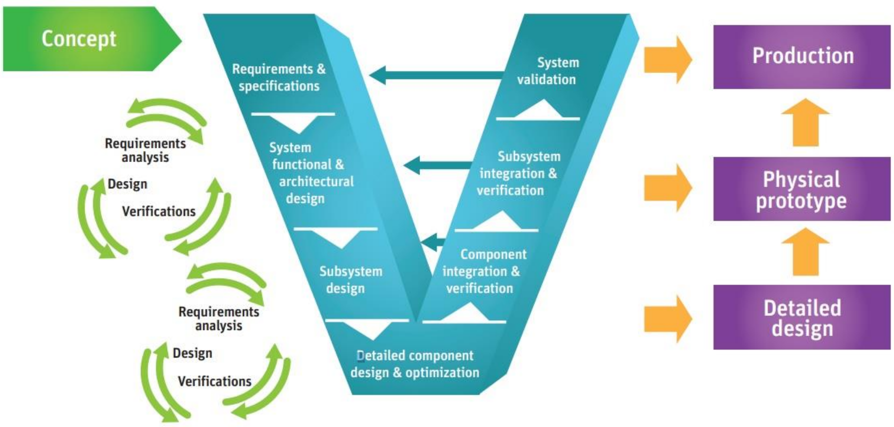

Figure 2. V-model

most of which are important part of the source of requirements, are still on going and it will be necessary to modify the requirements and architectural design basis accordingly in the future.

1.2 The need for a systematic approach

Many engineers have been designing their products intuitively, based on their experience, involving much trial and error. This approach is very unsystematic (i.e., lacking a definite plan) and overly time consuming. For this reason, experience gained from such practices cannot be easily reapplied to other similar issues. Although experience is important since it generates knowledge and information about practical design, experiential knowledge alone is not enough, as it is not always reliable, especially when the context of the application changes. Experience must be supported by systematic knowledge of design (Suh, 2001). Design has always benefited from the creativity, but this process must be augmented by amplifying human capability systematically through fundamental understanding of cognitive behaviour and by the development of scientific foundations for design methods (Suh, 2001).

In recent years, researchers and practitioners worldwide have recognized the importance of structured, scientifically based, and industrially tested theories and methods for product and process design and development. The research carried out by Clausing (1994) has sought the following goals: reduced development time, reduced product costs and increased value delivered to customers. A design process converts a need, a required functionality, into a product satisfying that need. However, the process is quite complex and requires the designer initiative and creativity as well the availability of a wide range of skills, methodologies and experience in attaining a solution. All design activities must do the following (Suh, 1990):

- Know the “customers’ needs”;
- Define the essential problems that must be solved to satisfy the needs;
- Conceptualize the solution through synthesis, which involves the task of satisfying several different functional requirements using a set of inputs such as product design parameters within given constraints;
- Analyse the proposed solution to establish its optimum conditions;
- Check the resulting design solution to see if it meets the original customer needs.

Design proceeds from abstract and qualitative ideas to quantitative descriptions. It is an iterative process by nature: new information is generated with each step and it is necessary to evaluate the results in terms of the preceding step (Albano, 1999). Suh (1990) sees design as a continuous interplay between what requirements the designer wants to achieve and how the designer wants to achieve these requirements.

1.3 Virtual reality supporting concept review

The generation of product concepts in early design stage leads to a selection phase in which is necessary to choose one more suitable solutions. Complex or important decisions should not be based solely on instinct. In the selection among alternatives, Multi Criteria Decision Analysis (MCDA) can help designers combine all the information and make informed decisions. In this context, virtual reality methodologies can be applied to make a scene more realistic as possible in order to support the presentation of a new concept. In particular, virtual reality tools give engineers the possibility to control shape, appearance (such as colour, lighting, reflection) and animation of objects, in order to make very realistic real-time renderings. The operator, immersed in the artificial environment, can benefit from a realistic sensation. The great advantage of these techniques to improve the realism is already known in the automotive field, in which the employment of virtual reality techniques for the conceptual design phase is widespread by now: such advanced design systems allow a remarkable saving of costs and time for the evaluation of several design solutions. Moreover, virtual reality techniques allow the designer to simulate its concept, in terms of design, or ergonomics and safety. Concept evaluation in virtual environment gives the opportunity to perform virtual experimentation of the design solutions.

The user-centred design, also known as participative design, it's important to improve quality not only in applications with industrial background, but also for non–industrial ones (Bruno & Muzzupappa, 2010; Di Gironimo, Matrone, Tarallo, Trotta, & Lanzotti, 2013; Yusuf, Georgakis, & Nwagboso, 2011). The purpose of the participative approach is to involve a group of experts to compare several alternative designs solutions in order to find an optimal one with the help of an immersive virtual reality environment. The immersion in a virtual environment is important to let the expert make both an aesthetic evaluation of the concept, and a functional evaluation of all the mechanisms; this is possible also because the user with the help of virtual reality can interact with the product and live an experience of product use. In fact, immersive simulations in virtual reality allow the designer to interact directly with the models to perform subjective analysis. Furthermore, the collaborative environment is important to perform the mix of competencies necessary to the development of the design activities; in the successive phases of the design the advantages can be measured in terms of overall time consuming (Di Gironimo & Patalano, 2008; Lanzotti, Di Gironimo, Matrone, Patalano, & Renno, 2009).

2 Materials and methods

2.1 Quality Function Deployment

To design a product, a design teams needs to know what they are designing, and what the end users will expect from it. Quality Function Deployment (QFD) is a multi-level analytical method to transfer the customer or market requirements into design requirements, parts characteristics and process requirements. QFD was developed by Akao in Japan in 1966 and is an important product development method dedicated to translate client requirements into activities to develop products and services. QFD was originally proposed, through collecting and analysing the voice of customer, to develop products with higher quality to meet or surpass customer's needs. QFD develops a new product, or a new version of an existing product to maximize customer satisfaction by integrating marketing, design engineering, manufacturing, and other related functions of an organization, considering such criteria as cost and technical difficulty (Delice & Güngör, 2009). The three main goals in implementing QFD are:

1. Prioritize spoken and unspoken customer wants and needs;
2. Translate these needs into technical characteristics and specifications;
3. Build and deliver a quality product or service by focusing everybody toward customer satisfaction.

One of QFD's main instruments is the House of Quality. The essence of the HoQ is a system to ensure that the development of the product is focused toward customers' satisfaction, and to guide enterprise managers and staff during the various stages of product development accurately into the related technical parameters. It can be considered as a graphic tool for defining the relationship between customer desires and the product capabilities. This process is represented by a succession of double entry "Whats/Hows" tables allowing the correlations between entries to be identified and prioritized. The basic structure of the HoQ is a table with "Whats" as the labels on the left and "Hows" across the top. The roof is a diagonal matrix of "Hows vs. Hows" and the body of the house is a matrix of "Whats vs. Hows". The structure of the House of Quality is illustrated in Figure 3.

The House of Quality may help designers to find creative solutions that satisfy all customers' needs. However, usually, designers have to trade off one benefit against another. The trade-off activity starts from the investigation of the relative importance assigned to each customer need; the weights are generally based on designers' direct experience with customers or on surveys and are displayed in the house next to each customer need usually in terms of percentages (Hauser & Clausing, 1988). The engineering features inserted into the House of Quality have to be improved collaterally. The necessary trade-off decisions starts from the roof matrix on top of the house, where the most critical information for engineers to address customer benefits are contained.

2.2 TRIZ

TRIZ is the abbreviation of "Theory of Inventive Problem Solving", in Russian "Teoriya Resheniya Izobretatelskikh Zadatch". TRIZ is an engineering problem solving toolkit which provides a methodology useful to systematically solve problems, in which the principles of good inventive practice are encapsulated in a general problem solving structure (Domb, 1998). TRIZ focuses problem understanding to the particular, relevant problem model and then offers conceptual solutions

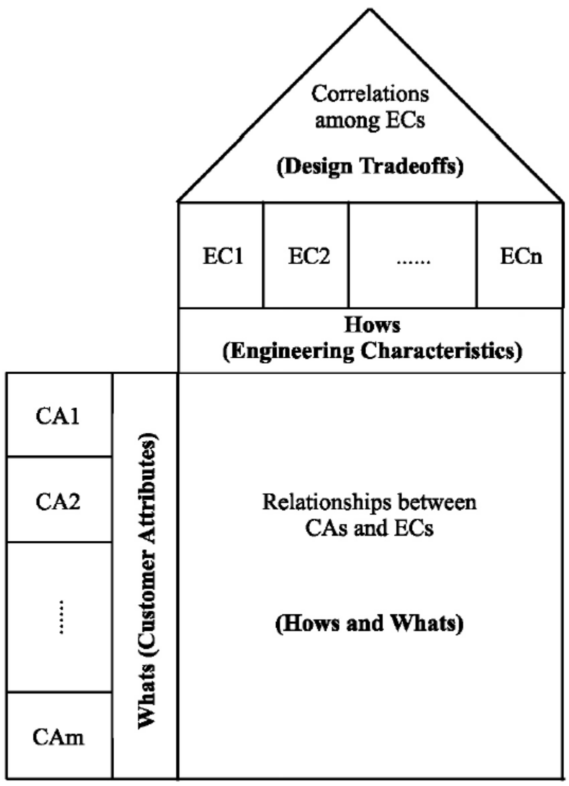

Figure 3. The structure of the House of Quality

to that model. With TRIZ is possible to save time, as the instrument lets the engineer focus on valid solutions to the problem and then develop those solutions (Gadd, 2011). The purpose of TRIZ is to overcome the psychological barrier in problem solving through the generalization of the specific problem to an analogous generic problem, for which a generic solution can be found. At this point, a specific solution can be identified, usually with the help of brainstorming sessions and experience. The use of brainstorming and technical knowledge is very useful because TRIZ works in a high level of abstraction (Terninko, Zusman, & Zlotin, 1998). TRIZ is a toolkit in which each tool covers an aspect of problem understanding and solving. Several recent papers show interesting applications of TRIZ theory, also in combination with other tools, to solve technical contradictions (Conradie & Consultores, 2005; Jiangnan & Shixiong, 2011; Wu, 2004; Xinjun, 2003).

2.2.1 TRIZ contradiction toolkit

TRIZ theory provides several techniques and methods, one of the most important being the contradiction matrix. The strength of this tool is to remove contradictions rather than finding compromises or trade-offs. During the problem solving activity, instead of a simple brainstorming activity, TRIZ theory brings 40 principles, widely available in literature, that suggest a direction for the innovation (Gadd, 2011). The steps to the solution are the following:

1. Define the problem and the elements that need to be improved;
2. In the contradiction matrix, map the elements of design in terms of the 39 parameters;
3. Identify the solution direction to solve the problem and the elements that are in contradiction with them;
4. Find inventive principles joining two characteristics in the contradiction matrix;
5. Develop special solutions based on the suggestions of the inventive principles.

2.3 Combination of QFD and TRIZ

In the past, only instruments like brainstorming were present to select ideas. These instruments represented the principal approaches to innovation. At present, to improve the design process of an organization there are other powerful instruments. QFD translates in the engineer's language all the relevant information provided by the customer, contributing in a customer-centric product design. The combination of QFD and TRIZ is the perfect complement in the process of developing a new product (Chaoqun, 2010). QFD can help designers understood what they should do to meet the needs of their customers, but it can't help to solve the problem of how to do this. Although QFD combines customer's needs with quality of the elements through the HoQ very ingeniously, some problems are present in product innovation design in practical applications. On the other hand, TRIZ provides several tools to solve difficult design contradictions; however, designers must find solutions based on their experience.

To overcome these limitations, several studies integrate QFD with TRIZ (Chin-Sen, Long-Sheng, & Chun-Chin, 2011; Su & Lin, 2007; Yamashina, Ito, & Kawada, 2002): this process enables the effective and systematic creation of new product functions. The combination of HoQ and TRIZ let designers satisfy customer demand and solve successfully varied technology contradictions. The product design process is aimed to find the design of new products, starting from conceptual design parameters, and then determine several technical solutions based on these parameters. House of Quality (as part of QFD) is used to determine the design parameters for the product concept through the customer demand; TRIZ solves the contradictions between the design parameters. Therefore, the integration of TRIZ and QFD is useful to find product specifications that satisfy the customer and solve conflicts that may exist between design parameters. Adding TRIZ to QFD there are drastic improvements in the innovation area of both the product and the process (Terninko et al., 1998).

In this integrated process, HoQ is built in accordance with customer's demands first, and then a conflict analysis of the negative correlation parameters in the correlation matrix is done. Each conflict belongs to a TRIZ category, that is determined according to different criteria, and the solution is found using TRIZ instruments. Each negative correlation found in the roof of the House of Quality is composed of two quality characteristics in conflict. These characteristics are translated into two TRIZ parameters, one improving, and the other worsening. The intersection of improving/worsening parameters in the TRIZ contradiction matrix provides a set of inventive principles that guide the inventive process. The solutions found with this approach can be developed in further steps of design.

2.4 CAD design

Parametric CAD software can be used in order to generate and evaluate product concepts. Inventive solutions provided by TRIZ can be designed directly into the software, adopting a top-down technique. The top-down logic is a typical approach to design complex products, due to the advantage of modelling parts automatically assembled in the right position without further operations (Lee & Gossard, 1985; Mantripragada & Whitney, 1998; Whitney, 2004; Whitney, Mantripragada, Adams, & Rhee, 1999). In software modules like the Assembly Design workbench of CATIA, Digital Mock-Up (DMU) inspection capabilities are also available to review and check assemblies. Starting from a set of geometrical references of the product, several components are designed with respect of the whole assembly, with particular attention to the relationship between the parts, in order to achieve the maximum degree of freedom making changes in further steps of the designing process. All the changes applied to the reference geometry produce an automatic change in the assembly geometry. Therefore, after the extensive work necessary to complete the CAD modelling, using the top-down approach is possible to change in any time product dimensions without any manual adjustment on the geometry, thus saving time (Di Gironimo & Patalano, 2008). Thus, the adoption of a top-down approach, allows the designer to have a complete view of the whole assembly, and making adjustments of the entire assembly in real time (Di Gironimo, 2012). Kinematic mechanisms, if present, can be created in simulator environments, to evaluate and simulate assembly motions. Adopting a top-down approach, the designer has a complete view of the whole assembly, and it is possible to make considerations and adjustments of the entire assembly in real time, saving time (Di Gironimo, Lanzotti, Melemez, & Renno, 2012).

2.4.1 Use of ergonomic tools in CAD environments

Recent studies show some advantages of the manikins' use in virtual environment and of the simulation of human tasks (Di Gironimo, Di Martino, Lanzotti, Marzano, & Russo, 2012; Di Gironimo, Patalano, Liotti, Conserva, & Paruccini, 2005; Di Gironimo, Patalano, & Tarallo, 2009; Di Gironimo, Pelliccia, Siciliano, & Tarallo, 2012). Recent studies have shown some advantages of using manikins in a virtual environment to evaluate the interaction of the product concepts with people and for the simulation of human tasks (Di Gironimo, Lanzotti, et al., 2012; Di Gironimo, Pelliccia, et al., 2012).

To assess the level of exposition to injuries, several indicators are commonly used during ergonomic evaluation. The main indicators used in this work are the Rapid Upper Limb Assessment (RULA), the Low Back Analysis (LBA), and the PEI (Posture Evaluation Index).

The RULA (*Work-related upper limb disorders: a guide to prevention*, 2002) allows to evaluate the workers exposition to the risk of hassles and/or upper limbs injuries (Di Gironimo, Mozzillo, & Tarallo, 2013). To use RULA is necessary to:

- Place the virtual manikin in the most stressed posture for the operation;
- Specify whether the posture is maintained for more than one minute (Static), repeated less than 4 times in one minute (Intermittent) or repeated more than 4 times in one minute (Repeated);
- Specify if arms are supported or person leaning;
- Specify if person checks balance;
- Assign an eventual load to the hands, specifying whether it is static or cyclic.

The Biomechanics Single Action Analysis enables the evaluation of the L4-L5 Compression, also known as LBA (Chaffin, Gunnar, & Bernard, 2006), that are the acting compression forces on the vertebral discs L4-L5 (low back) which limits are recommended from the NIOSH directive (Di Gironimo, Matrone, et al., 2013).

The PEI (Di Gironimo, Monacelli, & Patalano, 2004) integrates the results of LBA, the Ovako Working Posture Analysis (OWAS) (Karhu, Kansi, & Kuorinka, 1977), and RULA, in a synthetic a-dimensional index able to evaluate the "quality" of a posture.

$$PEI = LBA/3400 + OWAS/3 + RULA/5$$

In the PEI the LBA index is normalized through the NIOSH limit for the compression strength (3400 N); in the same way the OWAS and RULA indexes are normalized through their critical values, respectively 3 and 5. PEI can range between the minimum value 0.47 (i.e. no loads applied to the hands, values of joints angles within the acceptability range) and the critical value 3.00 (when all the ergonomic indexes get to the critical value).

2.5 AHP

While the combined use of QFD and TRIZ has been widely reported in literature, the use of decision-making techniques, combined with virtual reality, seems to be innovative in the evaluation phase. In particular, VR improves the interaction of designers with the virtual concepts, allowing an adequate subjective evaluation.

The comparison of concepts, their evaluation and eventually the choice of the best solution, can be performed using the Analytic Hierarchy Process (AHP). AHP is a technique developed by Thomas L. Saaty in the 1970s (Saaty, 1990). The technique is a multi-criteria decision making approach in which the factors that are important in making a decision are arranged in a hierarchic structure. Arranging goals, criteria and alternatives in a hierarchic structure is important to provide an overall view of the relationship between elements related to a decision process, and also to help decision makers understand whether the elements in each level are of the same order of magnitude, so that they can be compared homogeneously. The main advantage of using AHP lies in the analytical nature of the methodology (Di Gironimo, 2010). AHP allows not only to evaluate the weights of the different concepts, but also to prioritize the different quality elements. AHP works as follows.

After the main goal of the process is defined, the entire decision hierarchy should be designed. The main goal is connected to a set of criteria, which can be also subdivided in several sub-criteria. The alternatives to be evaluated are in the lowest level. Once the hierarchical decomposition of the problem is completed, the elements for each level of the hierarchy are compared in pairs, defining a matrix of weights (Di Gironimo, 2010). The process requires to take each pair of elements (A_i, A_j) and ask expert(s) to respond, with a ratio, to the pair wise comparison of "which of A_i and A_j is more important, and by how much (how many times)". Thus, the comparison between elements is made using a scale of numbers that indicates how many times more important (or dominant) one element is over another with respect to the criterion to which they are compared (Saaty, 2008). All the *n* elements involved in the comparison are placed on the rows and columns of the matrix, obtaining a square matrix (Di Gironimo, 2010). The generic element of the matrix of weights is the result of the pairwise comparison between two attributes using the scale reported in Table 1, and hence is equal to the ratio of the weights of the corresponding elements (Di Gironimo, 2010; Saaty, 1990). When judgments come from a group, to aggregate individual judgments into a single judgment, it was proved that the geometric mean, and not the arithmetic mean, should be used (Saaty, 2008). The generic element of the matrix of weights is hence obtained as the nth root of the product of the several judgments. When alternatives are measured on an objective scale, like meters or kilograms, a priority comparison on all the data available, without ascribing linearity to them, has to be made. The numbers should be interpreted using judgment and not mechanically; the judgment approach is the more effective procedure using AHP because the theory is descriptive, and needs interpretation (Saaty, 1986, 1990).

In a general decision making process, is not possible to evaluate the precise values of the elements, but only estimate them, considering estimates of these values given by experts who make small errors in judgment. The matrix of weights obtained is then an approximation of the real one (Saaty, 1990). Inconsistency of the matrix can be evaluated with a Consistency Ratio test (*CR*):

$$CR = \frac{CI}{RI}$$

The consistency index (*CI*) can be obtained from the following equation, where λ_{max} is the principal eigenvalue of the matrix of weights and *n* its dimension:

Table 1. The scale used to make comparisons with AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

RI is a Random Index, and its values can be estimated from matrices with random entries. The estimate of the weights is accepted if *CR* does not exceed 0.10 (Najib, 2012; Saaty, 1990).

2.5.1 Fuzzy-AHP

The decision maker's requirements may contain ambiguity and the human judgment on quality attributes may be imprecise (Di Gironimo, Matrone, et al., 2013). Thus, the crisp aspect of the conventional AHP seems inappropriate in depicting the uncertain nature of this decision phase (Melemez, Di Gironimo, Esposito, & Lanzotti, 2013). AHP can be combined with the fuzzy sets theory to consider uncertainties during the early stages of design and deal with the variables in verbal judgments. In fact, fuzzy interfaces to transform the linguistic variables into fuzzy numbers are often used to avoid the uncertainty brought by numerical voting.

The application of fuzzy methodology enables the decision makers evaluate the decisions based on both qualitative and quantitative data. For this reason, it improves the level of confidence of decision makers in giving interval judgments rather than fixed value judgments. In one possible approach, triangular fuzzy numbers can be employed for evaluating the preferences of one criterion over another. Then, by using the extent analysis method, the synthetic extent value of the pair-wise comparison is calculated.

Triangular numbers and fuzzy conversion scales employed in existing studies (Ayağ & Özdemir, 2006; P. Chen & Wang, 2009; Fu, Chao, Chang, & Chang, 2008; Perçin, 2008) can be used to perform pair-wise comparisons among the parameters. An example of the use of five main linguistic terms and the respondents' reciprocals is reported in Table 2. Linguistic terms are preferable because decision makers will feel more comfortable. For example, someone may consider that the cost component *i* is "absolutely important" compared with the component *j* under

Table 2. Triangular fuzzy conversion scale

Linguistic scale for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equal important (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more important (WI)	(1, 3/2, 2)	(1/2, 2/3, 1)
Fairly more important (FI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more important (VSI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important (AI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

certain criteria; decision makers may set $a_{ij} = (5/2, 3, 7/2)$. If element j is thought to be "absolutely less important" than element i, the pair wise comparison between j and i could be presented by using fuzzy number $a_{ij} = (1/u, 1/m, 1/l) = (2/7, 1/3, 2/5)$. Judges are asked to evaluate the relative importance of the evaluation criteria first, and then they are asked to compare the proposed solutions. Applying the extent analysis (Chang, 1996) to the results of a questionnaire, a weight is derived for each solution. The solution with the highest score is then selected as the best.

2.6 The Axiomatic Design approach

An effective product development process, supported by scientifically validated design theories and tools, is becoming an increasingly useful asset in industry for reducing lead times and costs as well as for improving quality (Tate & Nordlund, 1996). Some design methodologies available in literature deal with most of the product development lifecycle activities whereas other methodologies deal with the process of creating a solution to a stated need.

The Axiomatic Design (AD) (Suh, 1990) is one of such methods that provides a systematic approach to design by introducing some axioms and theorems, and also concepts such as domains, zigzagging and design matrices. Several key concepts of AD and its extension to cover the whole product development lifecycle, namely Axiomatic (or Trans-disciplinary) Product Development lifecycle (Gumus, Ertas, Tate, & Cicek, 2008), are well adapted to the need to have a process that provides a robust structure and systematic thinking to support design activities. In the early conceptual design stage, when information are not yet completed, the requirements for the project will come in from the various actors involved in the design activities. At the end of the design process, a solution is specified in terms of product and implementation (i.e., manufacturing) details.

2.6.1 The traditional Axiomatic Design

The AD provides a systematic and logical method for deriving, documenting and optimizing designs. Furthermore, it helps avoiding traditional design-build-test-redesign cycles for design solution search and for determining the best design among those proposed (Suh, 2001). The method gets its name from its use of design principles or design Axioms (i.e., given without proof) governing the analysis and decision making process in developing high quality product or system designs. The two axioms used in AD are:

- Axiom 1: The Independence axiom. Maintain the independence of the functional requirements (FRs);

- Axiom 2: The Information axiom. Minimize the information content of the design.

There are four main concepts in AD:

1. Domains;
2. Hierarchies;
3. Zigzagging;
4. Design axioms.

The four domains are generalized as customer domain, functional domain, physical domain and process domain. Design elements are associated with each domain. In the order listed, the elements within each domain are: Customer Needs (CNs); Functional Requirements (FRs); Design Parameters (DPs) and Process Variables (PVs). For each pair of adjacent domains, the domain on the left represents “what we want to achieve”, while the domain on the right represents the design solution of “how we propose to achieve it”. Therefore, the design process can be defined as mapping from the “what” domain to the “how” domain. Functional requirements (FRs) and design parameters (DPs) are developed to provide enough design information at the conceptual level and are decomposed until the design can be implemented. The decomposition is performed by zigzagging between the domains, starting from the “what” domain to the “how” domain. The FRs and DPs hierarchies are established to represent the product design structure through the decomposition process.

During the mapping process (for example, mapping from FRs in the functional domain to DPs in the physical domain), the designer should take the correct design decisions using the Independence axiom. When several designs that satisfy the Independence axiom are available, the Information axiom can be used to select the best design. The designers apply the Independence axiom by using design matrixes that represent the mapping between the domains.

The set of functional requirements that define the specific design goals constitutes a vector FRs in the functional domain. Similarly, the set of design parameters in the physical domain that describe the design solution also constitutes a vector DPs. The relationship between the two vectors can be written as:

$$\{FR_s\} = [A]\{DP_s\}$$

Where $[A]$ is the design matrix that characterizes the nature of the mapping.

Design matrixes and system architecture highlight the relationships between the functional requirements, design parameters and constraints; they can be used to evaluate the impact of proposed design changes as well as functional requirement and constraint changes.

2.6.2 Axiomatic Product Development Lifecycle (APDL)

The AD method provides a robust structure and systematic thinking to support PDL (Product Development Lifecycle) activities; however, it does not support the whole product development lifecycle (Tate & Nordlund, 1995).

Axiomatic Product Development Lifecycle (APDL) is a system engineering product development model proposed by Bulent Gumus (Gumus, 2005; Gumus et al., 2008) that extends the Axiomatic design (Suh, 1990) method. APDL covers the whole product lifecycle including early factors that affect the entire cycle, such as development testing, input constraints and system components. APDL model utilizes the systematic nature of the AD method in order to provide a systematic approach for product development lifecycle activities and management, and provide an iterative and incremental way for a team of trans-disciplinary members to approach holistic product development. APDL improves AD in the area of domain entity description and management and takes the AD method one step further to support the test domain of the product development lifecycle (Gumus et al., 2008). In APDL, one new domain and four new characteristic vectors are added to existing AD domains and characteristic vectors, supporting different development lifecycle activities such as requirements and change management throughout the whole product development lifecycle. A characteristic vector for System Components (SCs), that are the physical entities that provide the design solution stated in the DPs, is defined in the Physical Domain. The SCs hierarchy represents the

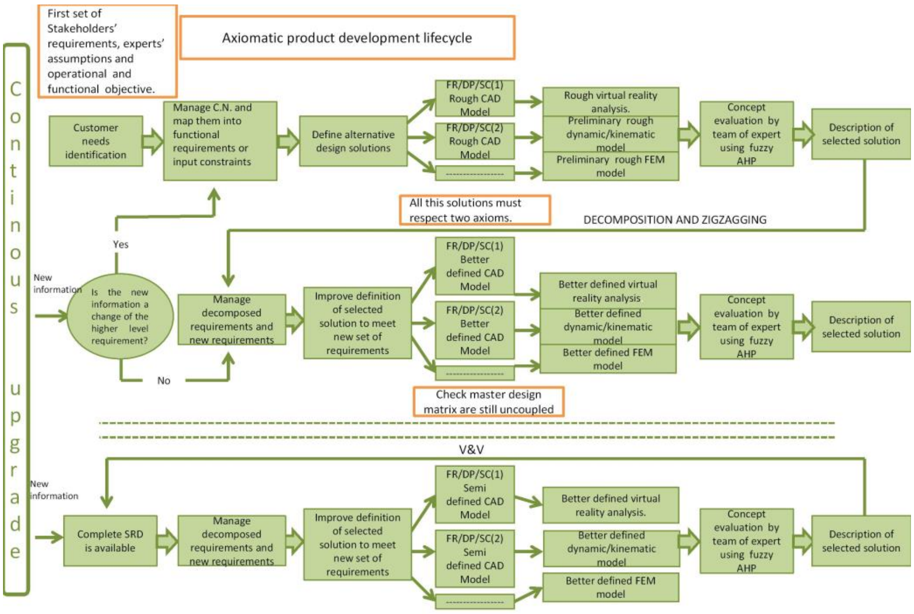

Figure 4. APDL process

physical architecture of the system. The Test Domain is added to the existing AD domains, and it contains the Component Test Cases (CTCs), that are used to verify the corresponding component that satisfies the allocated FRs, and the Functional Test Cases (FTCs). The APDL model proposes a V-shaped process to develop the detail design with a top-down approach, to complete the PVs, CTCs, and FTCs and to produce and test the product with a bottom-up approach as shown in Figure 4.

Once the FRs and the ICs are derived, they should be analysed to develop the system FRs, DPs, and SCs triplet that states the system objective, the proposed system design and the proposed system component. Then, the design decomposition and zigzagging process starts. Since the initial FRs can be at different levels of detail, they should be mapped to the FRs/DPs hierarchy during the decomposition process. Full integration of documentation as well as traceability throughout the development lifecycle should be provided. It is important to define standard templates for domain entities and for CNs, FRs, CTCs, and FTCs. The templates for documenting the domain entities and the mapping matrix are presented by Gumus (2005).

2.7 Discrete Event Simulation (DES)

Simulation is the best method for studying complex supply chains, where individual links interact with each other and interactions are driven by a combination of independent factors. Net productivity and randomly occurring delays can be modelled in order to represent the contingency of time requirements for each activity, and for the whole chain (Asikainen & Metsäyhdistys, 1995). Deterministic models can be used for the purpose, but they are much less realistic than proper stochastic models (Talbot & Suadicani, 2005).

In the field of simulation, a Discrete-Event Simulation (DES) models the operation of a system as a discrete sequence of events in time (Di Gironimo, Lanzotti, Peluso, & Renno, 2013). Each event occurs at a particular instant in time and marks a change of state in the system (Robinson, 2003). Between consecutive events, no change in the system is assumed to occur; thus the simulation can directly jump in time from one event to the next.

3 Case studies

3.1 Fusion engineering

The studies illustrated in this section refer to the application of systematic innovation methods to the concept design of complex mechanical systems related to important fusion engineering projects. In particular, we focused on core components of the “tokamak”. Tokamak is the acronym of the Russian words “TOroidal’naya KAmeras MAgnitnymi Katushkami”, which means toroidal chamber with magnetic coils, and it accomplishes the confinement of the plasma in a fusion reactor. A significant aspect in tokamak operations concerns how plasma occupies the available volume of the chamber. Two configurations are allowed: limited or diverted. In the latter, plasma legs intersect the plates of a particular metallic structure, namely the divertor, which operates as a pumping system of plasma impurities, concentrated in the scrape-off layer. The function of the divertor, as the names suggests, is to exhaust helium and plasma impurities from the reactor. The divertor, which represented the key component in the case studies illustrated below, is one of the most technically challenging components of any tokamak, since it is a plasma-facing component, directly facing the thermonuclear plasma. Our studies mainly focused on the following aspects:

- Improve the design of the divertor with respect to remote maintenance operations and systems;
- Design new systems to lock the divertor to reactor’s walls.

The remote maintenance system in a tokamak refers to all the equipment related to the maintenance operations of the machine. It also includes structural features in the tokamak that have great impact on the remote handling of the components. Remote handling enables a human operator to complete operations of inspecting, repairing and replacing of components without being physically present at that work site. During the operation in a tokamak, the thermo-nuclear reaction leads to rapid material damage and degradation of the components inside of the fusion reactor. Therefore, it is necessary to replace these components as part of a scheduled maintenance program. Remote handling (RH) is a fundamental aspect related to the tokamak. In order to maintain and repair the reactor, remote handling technology became the solution since the operation of the Join European Torus (JET) tokamak. With higher power production, it is even more crucial to continue the use of remote handling technology. The main handling devices are robotic manipulators, controlled by an operator through virtual reality, television and a wide range of specialist tools.

One of the most important components related to the operation and availability of the reactor is the cassette-reactor connection, or locking system. The locking system is related to the divertor replacement procedure and divertor remote maintenance process and equipment. The divertor is attached to toroidal supports integrated into the vacuum vessel of the reactor via a mechanical system which components consist of an inner locking, so-called “Nose”, and an outer locking, so-called “Knuckle”.

The case studies illustrated in the following sections are related to two important projects in fusion engineering: Fusion Advanced Studies Torus (FAST) and the DEMOnstration fusion power plant, DEMO.

Currently, one of the most promising projects is FAST (Pizzuto, 2010), test bed to support the International Thermonuclear Experimental Reactor (ITER) physical experiments and exploring methodologies and innovative solutions, in order to support the design of DEMO. The fusion agenda needs parallel R&D activities to reach these objectives in the scheduled time. It is widely accepted that a key role for the preparation and a rapid exploitation of ITER is the conception of one or more satellite tokamak experiments (Holtkamp, 2008). Such satellite experiments will also give an important contribution in testing new technologies. FAST is playing an important role in order to provide RH solutions.

DEMO will demonstrate the feasibility of energy production from nuclear fusion and will mark the very first step of fusion power into the energy market by supplying electricity to the grid. DEMO is intended to be the first fusion reactor capable to generate electrical power, demonstrate the large-scale production of electricity and lead the fusion into the industrial era.

3.1.1 Improving concept design of divertor support system for FAST tokamak using TRIZ theory and AHP approach

Introduction

This study (Di Gironimo, Carfora, et al., 2013) was focused on the application of the Theory of Inventive Problem Solving (TRIZ) to solve divertor Remote Handling (RH) issues found in FAST. The objective of this study consisted in generating concepts or solutions able to overcome design and technical weak points in the current maintenance procedure. Two different concepts were designed with the help of parametric CAD software, CATIA V5, using a top-down modelling approach; kinematic simulations of the remote handling system were performed

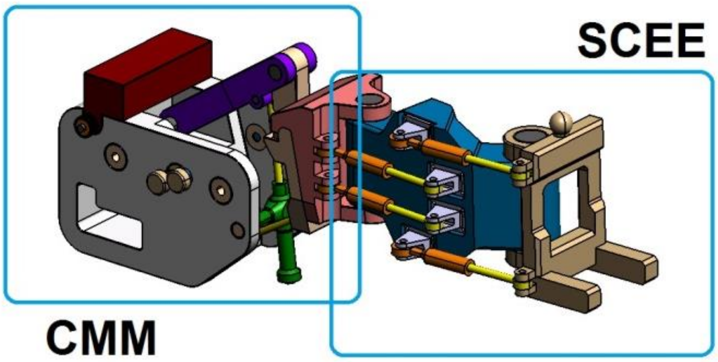

Figure 5. RH system for FAST tokamak

DMU capabilities of the software. The evaluation of the concepts was carried out involving a group of experts in a participative design approach using virtual reality, classifying the concepts with the help of AHP.

In previous studies, a RH arm for ITER was already proposed and designed and the first operations of maintenance were already simulated (Palmer, 2007). Analysing the ITER-like solution, critical aspects were observed and put under discussion, concerning the use of the system known as “knuckle”. This system is a mechanism that locks and unlocks the divertor in the outer side of the tokamak, and thus requires very accurate geometrical and dimensional tolerances. Moreover, it was observed that the knuckle might cause unwanted vibrations during the working period of the tokamak and that its maintenance might be difficult. In order to avoid these drawbacks a new solution was proposed in a previous study, aimed to propose a first concept design of the RH system, and a compatible divertor support system of FAST (Di Gironimo, Labate, et al., 2013). FAST RH system, illustrated in Figure 5, is mainly composed of two subassemblies, the Cassette Multifunctional-Mover (CMM) and the Second Cassette End-Effector (SCEE), the latter equipped with a further arm whose function consists in performing the critical operations of locking and unlocking the Cassette in its relative support system.

Starting from the analysis of an ITER-like solution of the RH system critical aspects and drawbacks were observed and put under discussion, concerning the use of the so-called “knuckle” system. First, geometrical and dimensional tolerances required high accuracies. Second, plasma operations generated unwanted vibrations, increasing RH complexity level. The analysis of an alternative solution introduced new conflicts with the remote handling system. In particular, the cantilever arm of the SCEE resulted partially obstructed in its movements by the presence of the divertor’s outer hook, this requiring a re-design of the entire system. In Figure 6 is showed the original design of the outer hook, together with the RH system (Di Gironimo, Labate, et al., 2013).

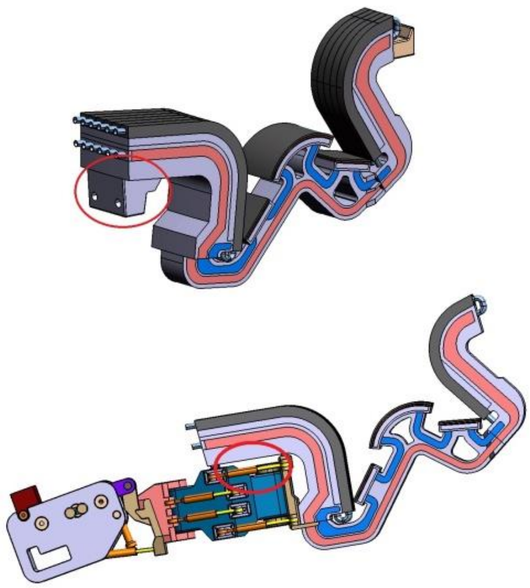

Figure 6. The conflict between the RH system and the outer hook

Materials and methods

In this study the components were designed in a smart way, solving technical conflicts observed during the simulation phases using the Theory of Inventive Problem Solving (TRIZ). The use of this engineering methodology suggested two different concept solutions, which were compared with AHP basing the comparison on the opinion of a panel of experts of the IDEAinVR Lab and the Divertor Test Platform 2 (DTP-2) team (Esqué, 2009), selecting a final concept.

The methodology adopted is illustrated in Figure 7. The whole process started with the identification of several design issues. Technical conflicts present in the considered system were translated in TRIZ language following the "contradiction matrix" approach, generating different concepts from specific solutions derived from TRIZ principles. The concepts were then designed in CAD software, performing kinematic simulations and analyses when required to compare the alternatives. Following the AHP methodology, a set of criteria was identified as a base for the comparison. The final evaluation session was carried out in virtual environment, involving several experts in the judgment.

Results

In this study, we generated new innovative solutions that overcame the existing difficulties, and innovative ideas were introduced on the final tokamak design. The use of TRIZ theory to solve the contradictions among quality elements, passed though the detection of the relative improving/worsening TRIZ parameters based on the engineering characteristics of the product in conflict. The intersection among improving and worsening parameters in the contradiction matrix gave

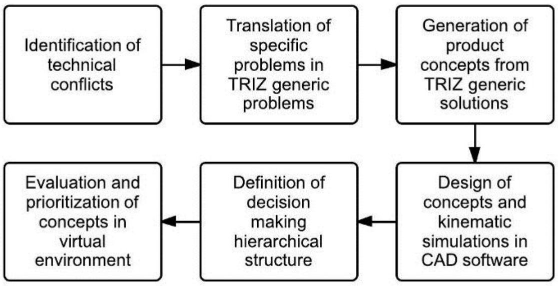

Figure 7. Flowchart of the methodology adopted

the TRIZ inventive principles to follow in order to find new possible engineering solutions. The main conflict came from the presence of the outer hook, which prevented the correct positioning of the SCEE for RH operations. TRIZ analysis was performed in order to smartly make room for the hook plate and the cantilever arm of the SCEE while the RH system is grappling the divertor.

The elements in the TRIZ contradiction matrix were chosen considering the functions in conflict in the system. For example, the selection of the first improving TRIZ parameter, "ease of operation", moved from the necessity to perform RH tasks minimizing the number of movements assigned to the whole system. At the same time, it was required that adjustments operated to the system in order to solve the conflict did not involve a significant change in the weight of the elements affected by the modifications. Thus, the worsen TRIZ parameter selected was "weight of moving object".

Table 3. Conflicts translated into TRIZ

TRIZ performance improved	TRIZ performance worsen	Inventive principles suggested
33. Ease of operation	1. Weight of moving object	3. Local quality 8. Anti-weight 10. Preliminary action 13. The other way around

Table 3 shows the result of the first TRIZ–related step, with the couple of TRIZ improving/worsening parameters for each conflict, and the inventive principles suggested finding special solutions.

All the principles found in the matrix of contradictions were taken into account in the brainstorming analysis, but not all of them were used to find new engineering solutions (Gadd, 2011). All the special solutions for the real system were generated via the principle "The Other Way Around", composed of three steps:

1. Invert the action(s) used to solve the problem;

2. Make movable parts (or the external environment) fixed, and fixed parts movable;
3. Turn the object (or process) “upside down”.

The first solution resulted from the third suggestion of turning the object “upside down”. The idea was to assign the role of “hook” to the outer support on the vessel.

The idea underneath the second concept came from the first suggestion of inverting the action used to solve the problem. It consisted in using, for the outer support, the same principle on which the inner support is based: contact between spherical surfaces. The first position of the RH arm was lowered of a certain angle, and the rotation of the CMM’s lift arm was adjusted. This solution allowed the divertor keeping the outer hook idea, creating space between the cantilever and the divertor.

The concepts were modelled into the Assembly Design workbench of CATIA. Following a top-down approach, a main references system was created to specify all the datum elements necessary to model the assembly.

In the first concept (Figure 8), the outer support was completely re-designed for its new scope. At the same time, the divertor was modified with material addiction, and excavated to create the groove that hosts the support. The locking system of the divertor is composed by two cap screws (18 mm diameter), which keep the divertor in 8mm compression in its position, pushing it on the inner part of the vessel, where the inner support is present. Thanks to the spherical cap of the inner hook, the entire structure is kept in position during the working phase of the tokamak. A suitable adaptation of the RH system to this new solution was necessary. With respect to the original design (Figure 10), the cantilever was shaped and carved according to the new support and the two lower ends of the hook plate were modified to properly hook the divertor in the lower part (Figure 11). The

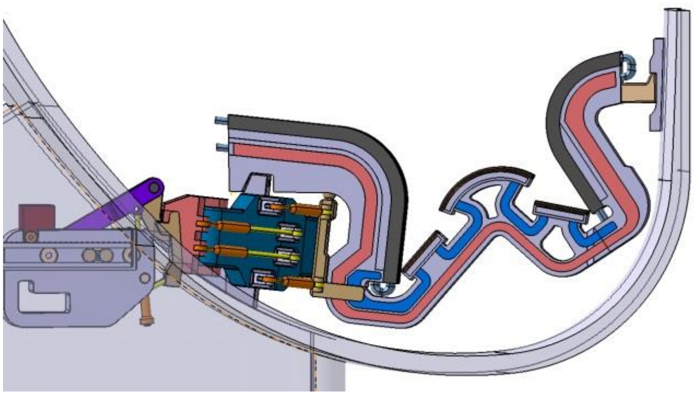

Figure 8. Concept I

sphere on the higher part of the hook plate was kept unchanged.

To design the second concept (Figure 9), starting from the divertor, material was added in two areas, in order to hook the divertor in the new position of the RH system. In order to avoid an excessive increase of weight of the divertor, the addiction of material was compensated on the two lower endings of the hook plate. As for the first solution, the cantilever was shaped, and it was necessary to cave it in the lower side, avoiding the interference with the vessel caused by the lower position of the entire RH system in the new configuration (Figure 12). With respect to the locking system of the divertor in this second concept, two pins (18 mm diameter) accomplish the function, together with extreme positioning precision of the components. This would require an extreme grade of precision in terms of tolerances.

In both the concepts, the inner hook and the inner support were not re-designed. After the design phase of parts, kinematic mechanisms were created to simulate the movement of the assemblies in order to evaluate the operation of the RH system.

In order to compare product concepts, a qualitative evaluation was performed by a group of experts to collect their opinion about the importance of several aspects of the concepts evaluated, to achieve a quality classification for the product variants. The problem of the choice between the two concepts designed was decomposed into several levels, identifying a set of criteria and sub-criteria in order to classify the alternatives. In the top level we identified the overall goal, the concept's choice. In the second level we determined three criteria, which contribute to the goal: *mass of the divertor*, *ease of manoeuvring of the arm* and *divertor locking system*. The last level was composed by the two concepts (Figure 13).

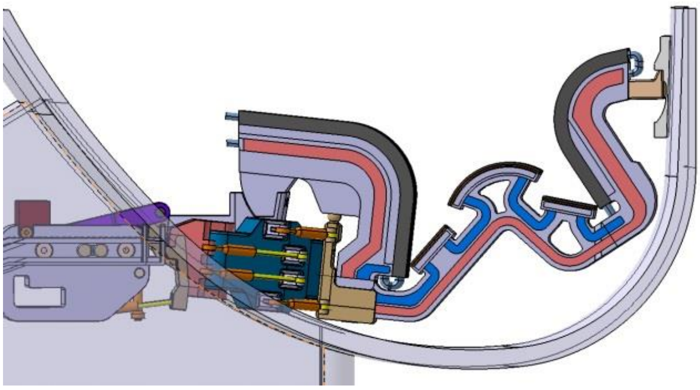

Figure 9. Concept II

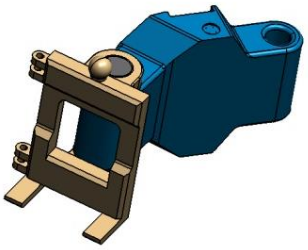

Figure 10. The original design for the SCEE

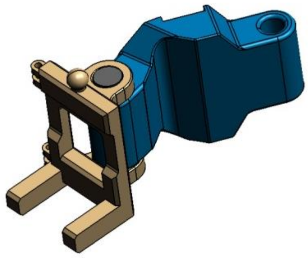

Figure 11. The SCEE re-designed for Concept I

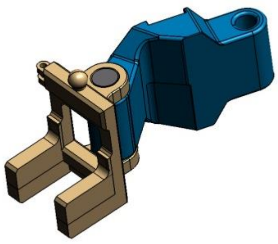

Figure 12. The SCEE re-designed for Concept II

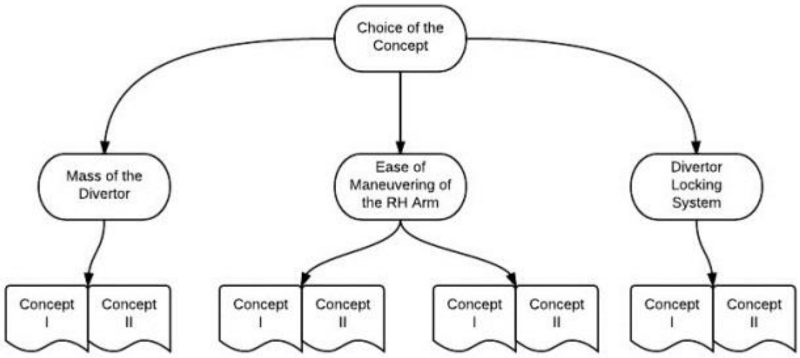

Figure 13. Hierarchical structure used for the comparison of concepts

The first criterion, *mass of the divertor*, was selected because, considering an estimated weight of the entire divertor of about 400 kg, adding material to the part could influence the design and sizing of other components like the supports of the divertor and the RH arm. Moreover, during the operation phase of the device, the mass of the divertor could be directly related to unwanted vibrations of the whole system. Since in both concepts the mass of the divertor was modified, the mass was considered valid for a comparison. To estimate the mass added to the concepts, we used the software CATIA, assigning the same material (steel) to the modified body of both new divertors. A mass increment of 43.8 kg and 44.7 kg was evaluated for the first and the second concept respectively. Hence, a the difference in terms of mass equal to 3.6 kg between both concepts, was detected, the first being slightly heavier than the second, which corresponds to an increase of about 1% on the total mass of the divertor.

The *ease of manoeuvring of the arm* criterion was selected because the two concepts were the result of two different ways to conceive the operations of RH. In the concept I, once the arm has hooked the component, the extraction of the divertor is performed moving back the entire system in the first step. This is possible due to existing clearances between the divertor and the outer and inner supports. After the first translation, the RH arm is able to take out the divertor from the tokamak thanks to the rotations of the CMM and of the SCEE. On the other hand, in the concept II, there are no clearances between the divertor and the supports and the spherical surfaces are in contact. For this reason, the movements assigned to the RH system are different. In order to remove the cassette, the first steps are the simultaneous rotations of CMM's as long as the release of the spherical cap of the inner hook, which is pushed against the inner support, is obtained. This motion is accomplished thanks to the spherical surfaces present in both the hook and supports of the divertor. For both the concepts, when the divertor is aligned with the vessel port, the RH arm scrolls back on the railways to complete the extraction of the cassette. The same movements are assigned for the insertion of the divertor, but in a reversed way. Two simulations of the divertor extraction were performed using the DMU Kinematics tool with the purpose of a comparison between the concepts. The number of commands needed to perform a complete RH operation was assumed as comparison criterion: 32 movements required by concept I, 42 by concept II.

The last criterion chosen for the comparison of the two concepts was the different *divertor locking system*. The divertor, during plasma operations is required to be in compression in its position to avoid unwanted vibrations and especially to the contact between adjacent divertors. In the first concept, the idea consists in using two cap screws keeping the two parts, the divertor and the inner support, linked in compression. Nevertheless, such a system would require a more complex un-screwing system. On the other hand, in the concept II, the divertor is kept in a fixed position by means of the contact between both surfaces. This would imply, for both the supports and the divertor hook, a zero-tolerance manufacturing with a very high grade of precision, which consequently increases the manufacturing cost.

In order to proceed with the application of the Saaty methodology, the two different concepts were presented to a group of experts according to a participative design approach. The evaluation phase was carried out in the IDEAinVR lab at the Department of Industrial Engineering of the University of Naples "Federico II", where the two concepts were showed on two different screens together with the two simulations of the RH process (Figure 14).

The purpose of this phase was to collect information via a survey, in which the

Figure 14. Comparison of concepts in the IDEAinVR lab

experts were asked to assign an adherence judgment to different sentences, with respect to an evaluation scale of importance, performing a pairwise comparison between several criteria and product alternatives. The geometric mean of the scores obtained in the surveys was used to build the 3x3 pairwise comparison matrix **A** reported in the following expression. This matrix passed the consistency test with a CR of 0.018, obtained from a *CI* of 0.00629, (while *RI*, for a 3x3 matrix, is equal to 0.58).

$$A = \begin{pmatrix} 1 & 0.14 & 0.2 \\ 7.3 & 1 & 0.77 \\ 5.54 & 1 & 1 \end{pmatrix}$$

From the comparison matrix, we derived the weights of the criteria. The AHP methodology allowed the estimation not only of the criteria weight relative to the single product concepts, but also of their global importance. In particular, the *mass of the divertor* was the less weighted criterion according to the fact that the two concepts differ only by 1% in terms of mass.

The knowledge of the weights of the three criteria allowed the evaluation of the final ranking for both the concepts (Table 4).

The solution with the highest score was hence found to be the concept I with a weight of 68%. This result was mainly related with the greatest importance, for the concept I, of both the *ease of manoeuvring* and *divertor locking system* criteria.

Conclusions

This work was focused on the optimization of the RH system for the FAST divertor, and the proposal of a first concept design of a compatible divertor support system. Since FAST is aimed to explore methodologies and innovative solutions to support the design of DEMO, the use of TRIZ methodology gave the valuable contribution to study new concepts able to overcome the issues identified during the previous design phases, based on ITER-like solutions. The simultaneous comparison of product alternatives in an immersive virtual reality environment has speeded up the review process. At the same time, the evaluation conducted using the AHP method allowed the prioritization of the alternatives based on qualitative and quantitative criteria selected for their importance in the choice. The resulting

Table 4. Results of the AHP evaluation

Criterion	Global weight	Concept I	Concept II
Mass of the divertor	0,07	0,4	0,6
Ease of manoeuvring	0,44	0,79	0,21
Divertor locking system	0,48	0,63	0,37
Total weight	1,00	0,68	0,32

concept proposed can be subjected to structural analyses and further engineering phases as next steps. The approach proposed in the study can also be exploited for future applications in nuclear fusion field, such as the design of FAST First Wall, with relative supports and RH systems.

3.1.2 Axiomatic Design approach applied to the design of the DEMO divertor locking system

Introduction

In complex situations, such as the early stage of the DEMO project, the design process starts when the requirements are not completely defined from the beginning. As the starting point of DEMO reactor design and development, requirement elicitation is considered as paramount activity across all the tasks within EUROfusion programs. In order to overcome these difficulties, in this study (Di Gironimo, Lanzotti, Marzullo, Esposito, & Carfora, 2015) we proposed a design process for drafting solutions in an “incomplete requirements environment”. In this kind of approach, the information will be completed during the design, as this situation may occur in complex projects during early conceptual design stages. In this work an innovative methodological approach was applied to the initial phase of conceptual design activities for the DEMO divertor-to-vacuum vessel locking system to propose new innovative solutions that could overcome the difficulties in applying the ITER principles to DEMO. Due to the lack and the uncertainty of the requirements in this early conceptual design stage, the aim was to propose an innovative design concept to be developed in greater detail as the information will be completed.

Materials and methods

The methodology adopted in this study has been developed so as to minimize the risks related to the uncertainty and incompleteness of the requirements, and considering that the requirements will be refined and completed during the process. The process, is an iterative, incremental, participative and requirements driven process. It was developed according to the design process roadmap proposed by Tate and Nordlund (1996), and it is based on the theories of AD and APDL (Gumus, 2005). Fuzzy-AHP was used as a tool for decision-making.

The approach proposed in this work was focused to adapt the requirements’ management in an incomplete information environment. In order to meet the problems derived from the ambiguity and the uncertainness of requirements in this early phase of conceptual design, all the process was performed highlighting the importance of the human factor and the contribution of experts. The panel of experts participated in the early phase of eliciting the first fundamentals customer needs, proposed some conceptual solutions and evaluated the most suitable design against the first set of generic assumptions and functional requirements. Due to the high level of abstraction characterizing the early phase of conceptual design, several solutions could be equivalent about the information content, or solutions that are more adapted to future requirements may be rejected too early. Therefore we selected Fuzzy-AHP as a multi-criteria decision making tool to obtain a final concept.

Results

As a first step, meetings and discussions were carried out with stakeholders and experts, to understand the different needs that DEMO divertor locking system shall meet compared to the ITER locking system. Due to the early nature of this conceptual stage the aim of these meetings wasn't the production of an official System Requirements Document (SRD) but the elicitation of a first set of requirements and experts' assumptions essentially based on the extrapolation of the studies on ITER RH process to DEMO. The main needs and experts' assumption emerged from preliminary project meetings were the following:

- Locking mechanism shall withstand operational radiation level;
- Divertor components are not planned to be re-used and refurbished like in ITER. That may affect the component design since the cassettes are used just once and do not require gentle handling;
- The cassette shall be electrically connected to the vacuum vessel via the inner and outer locking system;
- The locking system shall be compatible with remote installation and disassembly during divertor maintenance;
- Locking/unlocking operations require ITER-like robotic manipulators;
- The locking system shall be compatible with the transfer cask and RH geometries;
- Since it affects reactor availability, the locking system shall have short maintenance time. It means that the locking system shall provide simple, robust and time saving operations;
- Inner locking shall be a ITER-like, nose-hook mechanism;
- Outer-locking simplification is necessary due to harsh operation conditions, which set higher requirements to the locking and rescue ability;
- Outer-locking mechanism is designed in such a way that it generates preloading with a simple mechanism to remove any clearances and avoid "shaking" due to sudden change of the magnetic field;
- The outer locking system should be able to generate preloading applying a force of 10-15 tons to provide the cassette a displacement of 5mm;
- Outer-locking shall allow small rotations due to thermal expansion;
- The Locking System(LS) shall be designed to carry the maximum halo and eddy currents in case of VDEs;

- Magnetic forces are not yet known, but scaling the forces of ITER with the planned performance factor to DEMO give some estimate of the magnitude of the forces (scale factor = 1.4);
- It is needed that the locking systems carries load in all directions due to magnetic field;
- A rough test load could be taken extrapolating from ITER: F = 0.7 MN × 1.4 = 0.98 MN;
- Multilink attachments should be made of INCONEL 718; divertor to vacuum vessel locking system should be made of BRONZAL (Ni-Al bronze);

Even if we would not yet call these descriptions a set of requirements, they certainly are the forerunner of what will be defined as official requirements.

Concept solutions were designed in CATIA V5 using a top-down modelling approach in assembly environment. Adopting a top-down approach, the designer has a complete view of the whole assembly, and is possible to make considerations and adjustments of the entire assembly in real time (Di Gironimo, Franciosa, & Gerbino, 2009; Di Gironimo, Lanzotti, et al., 2012). The first solution generated during brainstorming sessions is shown in Figure 15.

The first concept idea was to preload the cassette pushing in a tool with a spherical surface. The spherical surface on the tool has a smaller radius than the spherical surface formed on the cassette, so that it is possible to provide the preload and the relative displacement of 5mm. All degree of freedom are locked by the socket engagements formed on cassette and supports.

The idea underneath the second concept was to taking advantage of the mass of the cassette using a gear arrangement to preload it, and then insert an “I” shaped tool able to withstand vertical and radial loads. The solution is shown in Figure 16.

As well as in the solution II, also for the third concept (Figure 17) we exploited the mass of the divertor, using a “cam” arrangement instead of the gear. The principle of operation is the same as the previous solution.

We developed other solutions during the generation of conceptual alternatives, but the three described above were the ones selected by the experts during the brainstorming sessions as the most promising and feasible.

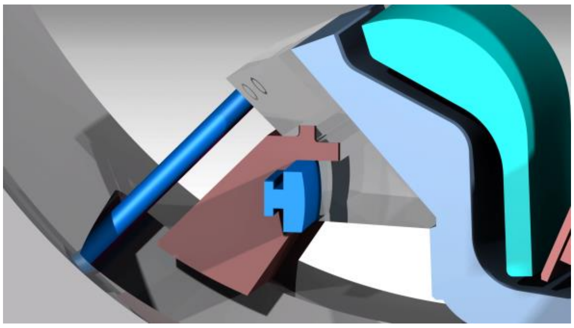

Figure 15. Concept I

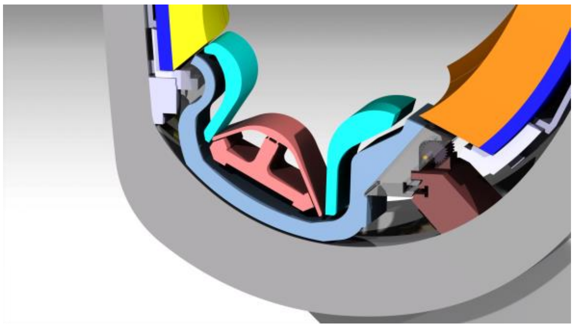

Figure 16. Concept II

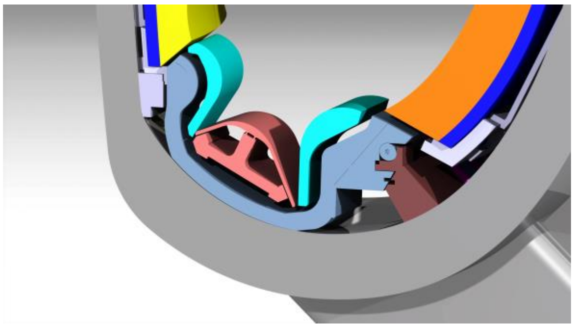

Figure 17. Concept III

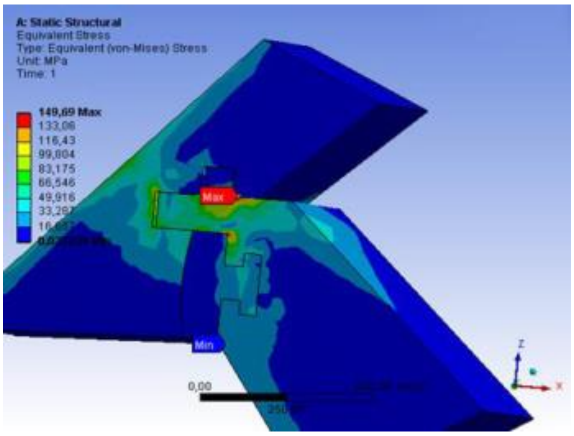

Figure 18. Equivalent Von-Mises stress (Concept I)

A preliminary FEM analysis was performed on the concepts to better understand the structural feasibility. This analysis, acting as a more objective way to evaluate the structural robustness of the different solutions, supported the subsequent evaluation stage that was carried out on these three concepts. FEM analyses were carried out using ANSYS Workbench, release 14. The models, designed in CATIA V5, were imported in the software, and the different contact areas were appropriately defined (results of the analysis for the Concept I are shown in Figure 18).

Table 6. Evaluation criteria

ID	Criteria
C1	Simplicity (mechanical and of operation)
C2	Structural Robustness
C3	Ability to preload cassette

Table 5. Fuzzy linguistic variables

Linguistic scale for importance	Abbreviation
Absolutely more important	AMI
Very strongly more important	VSMI
Strongly more important	SMI
Weakly more important	WMI
Equally important	EI
Weakly less important	WLI
Strongly less important	SLI
Very strongly less important	VSLI
Absolutely less important	ALI

Concept evaluation was carried out adopting the Fuzzy-AHP methodology, as previously mentioned. Two different teams of experts were involved in the evaluation: the first was the "DTP-2" team at VTT technical research centre of Finland, which was asked to fill the first section of the questionnaire. It covered the section about the "preference", in which the selected evaluation criteria were pair-wise compared. The chosen criteria are showed in Table 6.

Decision makers replied their preference about the criteria using Fuzzy Linguistic Variables shown in Table 5.

After converting the results obtained into triangular Fuzzy numbers, getting the average values and applying the extent analysis, we calculated the weight vector with respect to the decision criteria C1, C2, C3: $W = (0.3477; 0.343; 0.309)$. The pair-wise comparison among conceptual alternatives was carried out in IDEAinVR Lab of the Department of Industrial Engineering in the University of Naples "Federico II" (Di Gironimo, Carfora, et al., 2013), where a team of 25 engineers compared the alternatives with respect of each criteria using the fuzzy linguistic variables (Figure 19).

Applying the extent analysis, the results of the questionnaire were used to estimate weights of each candidate under each criterion separately. Finally, adding the weights per candidate multiplied by the weights of the corresponding criteria, a final score was obtained for each candidate (Table 7).

Figure 19. Concepts' evaluation in VR lab

Table 7. Final scores

Concept alternative	Score
Concept I	0.40
Concept II	0.31
Concept III	0.28

According to the final scores, it was clear that Concept I was the preferred alternative that we selected as the starting point for further design activities.

Conclusions

The present work was focused on the conceptual design stage in DEMO divertor-to-vacuum vessel locking system. Due to the early nature of design activities on DEMO, requirements are still uncertain and incomplete. For this reason in this study we proposed a design process for drafting solutions in an incomplete requirements environment. The method proposes a systematic manner to achieve solutions in the early phase of conceptual design stage in complex situations, limiting the risks arising from the lack of requirements and proceeding iteratively, refining and completing the requirements. According with this process, some solutions for the DEMO divertor locking system were proposed and generated with the help of CAD software. A FEM analysis was carried out as a first objective evaluation to support the evaluation process conducted following the Fuzzy-AHP method. Two experts' teams were involved during the requirements elicitation, concepts generation and concepts evaluation: the "DTP-2" team in VTT Technical research centre of Finland and the ENEA and IDEAinVR team of CREATE Consortium. In particular three concepts were generated, analysed and then pair-wise compared in VR; with this approach it was possible to have a simultaneous vision of the two solutions showing them on two different screens. Taking into account the results from FEM analysis and Fuzzy-AHP, the final concept chosen will be further detailed in future studies. The optimal concept selected in this work represents the starting point for subsequent iterations, in which the decomposition will proceed to more detailed levels and requirements will be completed. At the end of the process a SRD will be completed and a detailed design of locking system will be available.

3.1.3 Supporting the design of the DEMO divertor Remote Handling system using a FMECA approach

Introduction

The objective of this work was to identify possible and credible failure scenarios in the divertor cassette handling system of the DEMO fusion power plant. For this purpose, we started a Failure Mode, Effects and Criticality Analysis (FMECA)

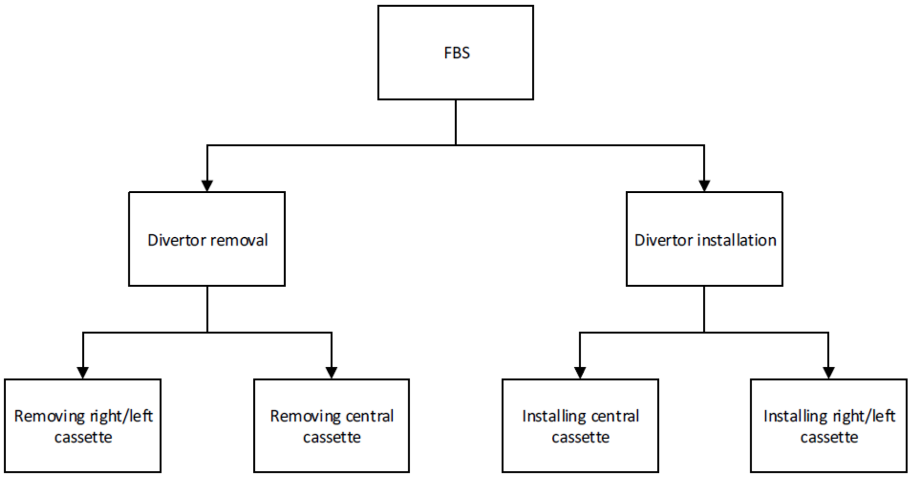

Figure 20. FBS structure: operations and tasks

analysis on the divertor cassette handling concept design. We started with a preliminary Functional Breakdown Structure (FBS) which was developed specifically for the operations of installation and removal of divertor cassettes. The whole FMECA analysis was conducted on the reference design of the DEMO divertor maintenance port in a particular configuration (inclined 45°). This study has been designed to be compliant with Reliability, Availability, Maintainability and Inspectability (RAMI) requirements in DEMO systems. In this early stage of the design phase we considered a slightly different and more feasible approach from the standard FMECA procedure.

Materials and methods

We adopted a functional FMECA approach as described in ITER RAMI analysis approach. The purpose was the identification of failure modes in the concept considered, and the identification of the associated risk. Considering the conceptual nature of the study, we skipped the traditional Product Breakdown Structure (PBS) due to the lack of detailed information about system components. Instead, we preferred to start with a FBS, which gave us the opportunity to identify all operations, tasks and functions related with our concept. This came useful at the end of the analysis to compare several functional aspects with respect to criticality against failures. Failure modes were identified together with their envisioned causes and implications regarding overall operability, nuclear safety, recoverability and rescue-ability, and protection of investment. A functional analysis was carried out to provide a systematic understanding of system functions for the FMECA analysis. We described the main functions of the system considered and decomposed them gradually to lower level functions performed by sub-systems and components. Functional analysis provided a systematic search structure for analysing functional failure modes. Furthermore, it provided knowledge on functional inter-relationships that facilitated the assessment of the effects of the poten-

Table 8. Failure effects categories

Implication category	Description
Overall operability (O)	Failure can be bypassed by non-routine operator action or failure renders RH equipment/system unable to meet certain requirements set for its operation, e.g. process speed or accuracy. Repair of the failed RH equipment can be post-poned until the ongoing task is completed.
Nuclear safety (S)	Failure event induces a containment breach (a potential release of radioactive material to environment) or a nuclear-related safety hazard for plant personnel or environment.
Recoverability (RC)	In the event of failure, the ongoing task needs to be aborted. The failed RH equipment can recover itself to a safe area without help of additional systems.
Rescue-ability (RS)	In the event of failure, the ongoing task needs to be aborted. Deployment of additional/external system(s) is required to recover the failed RH equipment to a safe area.
Protection of investment (I)	Failure causes damage on RH equipment environment, e.g. other equipment of the RH system, or the ITER machine.

tial failures/failure modes. FBS provided a top-down decomposition of the functions of the considered system on multiple levels in a hierarchical manner. We considered the following levels:

- Operations
- Tasks
- Sub-tasks
- Functions

The first two levels are described in Figure 20.

For each leaf of the hierarchy (functions) a number of failure modes equal or greater to zero were defined. Each failure mode identified at least one failure effect and at least one failure cause. An effect category was identified as well. The identified failure modes were categorized in the FMECA table according to their envisioned implications in terms of: overall operability (O); nuclear safety (S); recoverability (RC); rescue-ability (RS); and protection of investment (I). Definitions introduced and applied for the effect categories are shown in Table 8.

In order to make clear distinction between implication categories, Recoverability (RC) and Rescueability (RS) were identified to indicate failure cases in which the on-going task needs to be aborted. Failures graded into the Operability (O) category would allow the on-going task to be completed before the failed RH equipment is transferred for repair. Recoverability and Rescue-ability differ from each other in that, in the latter, deployment and use of system(s) additional/external to the failed equipment is required to recover the failed equipment for repair.

Table 9. Occurrence rating scale

Value	Description	MTBF	λrisk / year	λrisk / hour
1	Very low	> 2000 years	< 5E-4	< 5.7E-8
2	Low	> 200 years < 2000 years	> 5E-4 < 5E-3	> 5.7E-8 < 5.7E-7
3	Moderate	> 20 years < 200 years	> 5E-3 < 5E-2	> 5.7E-7 < 5.7E-6
4	High	> 2 years < 20 years	> 5E-2 < 5E-1	> 5.7E-6 < 5.7E-5
5	Very high	> 10 weeks < 2 years	> 5E-1 < 5	> 5.7E-5 < 5.7E-4
6	Frequent	< 10 weeks	> 5	> 5.7E-4

ITER RAMI Analysis Programme applies Occurrence and Severity ratings for assessing the importance or "criticality" of the failure modes identified in relation to the basic functions. Occurrence refers to the manifestation probability of the causes identified for the failure mode. It obviously depends on reliability performance of the system elements needed for the function. A generic Occurrence rating scale is shown in Table 9. The ratings are based on specified ranges in terms of constant failure rate λ_{risk} and corresponding Mean Time Between Failures (MTBF) values (equal to $1/\lambda_{risk}$ per year). The hourly scale λ_{risk}/hour in the following table applies calendar hours as the time reference (e.g. 1 year equals to 8760 hours). Severity refers to the magnitude of harm caused by the envisioned effects of the failure mode on the system or the environment in which it operates. ITER IO has defined a severity rating scale, shown in Table 10, in which severity is related to the foreseen duration of time needed to return the system to a state at which normal operations can continue after envisioned failure manifestation. The value of unavailability is expressed a Mean Time To Repair (MTTR). Time of unavailability refers to the unavailability of the system to provide its operations because of a failure. This indicates a delay in completing the task. Depending on the situation, part of this time may or may not get transformed also to unavailability time of the DEMO machine. Severity of failure scenarios leading to damage to the facility may be assessed similarly, considering the foreseen time needed after a failure incident to restore and commission the facility back to its fully functional state.

Table 10. Severity rating scale

Value	Description	Unavailability (MTTR)
1	Weak	< 1 hour
2	Moderate	> 1 hour < 1 day
3	Serious	> 1 day < 1 week
4	Severe	> 1 week < 2 months
5	Critical	> 2 months < 1 year
6	Catastrophic	> 1 year

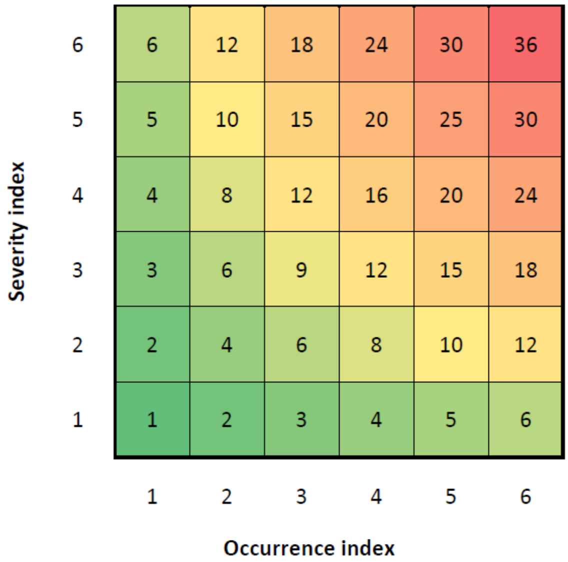

Figure 21. Criticality plot

We evaluated risk ratings basing them on a Criticality matrix plotting the failure scenarios by their assessed Occurrence and Severity rates. Criticality index values were calculated as the product of the Occurrence and Severity rates. Criticality values are shown in Figure 21.

Criticality thresholds were defined so that criticality index values 13 and 7 are defined as generic threshold values for depicting "Major" (i.e. > 13) and "Minor" (i.e. < 7) risk items. Thus, risk rating belonging to "Major" (i.e. red category), "Medium" (i.e. yellow category) and "Minor" (i.e. green category) levels were applied to sort the identified failure modes and scenarios according to the necessity for preventive and/or protection actions to reduce the associated risk. "Major" implies that actions are required/necessary, "Medium" that actions are recommended, and "Minor" that actions are optional.

Severity assessments regarding the effects of failure consider the credible worst case. They are based on engineering judgments of the study group regarding the expected time required after the failure to complete the current task and restore the system to a state at which normal operations can continue.

Occurrence rate assessments regarding the associated failure cause are based on expert judgments of the study group, reflecting the current level of design detail. The Occurrence rating scale previously specified has a low resolution. This implies that, in the worst case, reduction of the failure rate to onetenth of the initial value would be required to reduce the occurrence rate by one level.

Results

We collected a total of 680 failure modes during this analysis, from which 510 were classified in the recoverability category and 170 as rescue-ability category. Thus it represents a ratio of 25% of rescue-ability, against 75% of recoverability cases. While considering only the rescue operation, the FMECA shows that 35 cases got a criticality index above 10. From those 35 cases, most of those failures are related to control system about 57%, while only 17% for Hydraulic system failure, 14% for Mechanical failure and finally around 12% for Electrical failure. 30% of the failure causes are related to Electrical or Hydraulic systems, when only 14% are related to Control system or Mechanical systems. Positioning systems may cause 12% of the failures.

Conclusions

Considering that this study was conducted on a conceptual design level, deeper development of the FBS should come after the addition of further inputs. Moreover, FMECA will be re-iterated during the design phase and it highlights most critical functions of the designed system. The results of this study will help to lead the design process since it has highlighted critical areas of the design concept. Therefore, design efforts have to be concentrated on those critical aspects in order to improve the proposed design and thus reduce the criticality index of those failures.

3.2 Forest engineering

This section contains some studies aimed to the design of innovative forest equipment dedicated to contexts in which the use of highly mechanized machinery is low or absent. Thanks to the collaboration with the Forest Engineering Department of the University of Bartin (Turkey) and the Italian Trees and Timber Institute (CNR – IVALSA), we focused our efforts on farm tractor logging, which is a particularly low-mechanized type of logging with many constraints to the design of equipment, and on chipping operations for biomass collection. Our study areas were chosen in the north-western region of Turkey and in mountainous regions in northern Italy.

The application of mechanized equipment for harvesting purposes, in most regions of Turkey, like in other developing countries in the world, is currently low due to the fact that the labour cost is low and the fuel costs are high (Akay, Erdas, & Sessions, 2004). Forests are generally located in mountainous areas with difficult terrain conditions (Tunay, 2006). Forest machinery productions are of various types and dimensions and forest machines for Turkish forestry are purchased on the foreign market (Ozturk, 2010). Forest machines and equipment are usually designed to suit the working conditions of the manufacturer’s home country; therefore, when purchasing these machines, it is not sufficient to make decision on the basis of factory data and on their productivity found in foreign literature (Sabo & Porsinsky, 2005): the reason lies in specific relief, climate features of Turkish forests, as well as in diversity of tree species, condition of stands and manner of forest management. The harvesting system has to be chosen balancing it for the forest's characteristics, depending on machine type and intensity of the harvest operations to reflect variable factors that affect the productivity of the equipment. In a study by Akay et al. (2004), based on the data representing economic conditions in Turkey, it is reported that the forwarder system produce wood at a lower cost than cable skidder systems. Forwarders are used to transport short-wood or cut-to-length logs clear of the ground; they represent a good solution in the case of longer travelling distances and larger payloads. In the last years, adapted farming tractors and forest semi-trailer were developed (Horvat, Spinelli, & Susnjar, 2005). Agricultural tractors are cheaper to buy and operate than purpose-built forest machines, although they cannot achieve such large plans or high outputs (Jones, 1996). Furthermore, the investment level for a tractor and trailer combination is substantially lower than for a conventional forwarder (Russell & Mortimer, 2005). Finally, the tractor-trailer combination should be used as a complement to the main extraction fleet and where are required hauling operations (Spinelli, Owende, Ward, & Tornero, 2004). Farm tractor logging can be limited by some factors including terrain conditions, ground slope, and timber size (Akay, 2005). The main concern when talking about forest harvesting operations is probably the danger of lateral rollover; another significant problem related to harvesting operations is the soil damage. To minimize the forest soil damage, timber should be forwarded. Forwarders are large vehicles, that need to get close to the processed assortments because they are equipped with hydraulic crane; for this reason they can't be used in situations in which there is a high density of the stand (Horvat et al., 2005). The tractor-trailer combination should also be able to move inside the forest without colliding with stand trees or plants.

3.2.1 Concept design of an innovative trailer

Introduction

The main objective of this study (Melemez et al., 2013) was the design of a timber trailer capable of manual loading operations and suitable for rough terrain conditions, to be used in combination with an agricultural tractor. The trailer had to be used to carry logs having specific dimensions, for logging extraction operations, secondary transportation and agricultural activities, ensuring integrity to soil and plants inside forest area, and the prevention of rollover in high slope terrain conditions.

This study was conducted in the western Black Sea Region, one of the regions of Turkey that is rich in forest resources. Harvesting operations are performed using traditional methods, employing mostly manpower for skidding and tractors for winching and skidding. The application of advanced mechanized harvesting is limited since harvesting machines are very expensive and they have negative effects of mechanization on the workforce. The harvesting operations are also limited by rocky, rough and steep terrain. The ground slope of the region ranges from 30% to 60%.

Materials and methods

The first step of the process, illustrated in Figure 22, was the collection of the most important customer needs through a questionnaire based on a Likert scale. The survey provided a better understanding of what customers wanted and assisted the designers to focus on the most important product attributes to be improved (Y. H. Chen & Su, 2006; Cormican & O'Sullivan, 2004; Gustafsson, Ekdahl, & Edvardsson, 1999; Kumar, Venkatesan, & Reinartz, 2006; Kuo, 2004). The Likert questionnaire was composed of several sentences, for each of them the respondent had to provide an evaluation of his level of agreement, so that it was possible to categorize the customer requirements based on the importance given by the respondent (Shneiderman, 1998).

In order to translate information given by customers into functional requirements, we used the House of Quality, and in particular the study focused onto the top part of it where are contained the “HOWs”: the translation of every customer need into one or more global quality characteristics (Sørensen et al., 2010; Yeh, Huang, & Yu, 2010).

Customer needs found after the survey analysis were inserted into the left column of the House of Quality, because generally customer needs are reproduced in the customers’ own words (Hauser & Clausing, 1988). We found a set of measurable quality characteristics of the product in order to translate the selected customer needs into functional requirements to be designed. Each engineering parameter affected one or more customer attributes, and was placed in the top row of the HoQ.

The next step was the identification of correlations between the various quality characteristics, with an evaluation of the degree of relationship inside the main matrix of the HoQ. In the body of the matrix, the relationship matrix indicated how much each engineering characteristic affected each customer attribute. On the roof matrix of the HoQ, we found correlations between functional requirements, with particular interest in the negative ones, to identify which parameters were mutually affected by making changes. Negative correlations between engineering characteristics found into the roof of the House of Quality, if present, were solved with the TRIZ contradiction toolkit (Terninko et al., 1998). Inventive solutions provided by TRIZ analysis generated several product variants that were designed in parametric CAD software adopting a top-down modelling approach. Once product concepts were designed, we performed a quantitative evaluation using DMU and ergonomic CAD tools, in combination with process simulation software. For the evaluation, we chose a set of parameters related to quality elements considered in the House of Quality. For the evaluation of the interaction with peo-

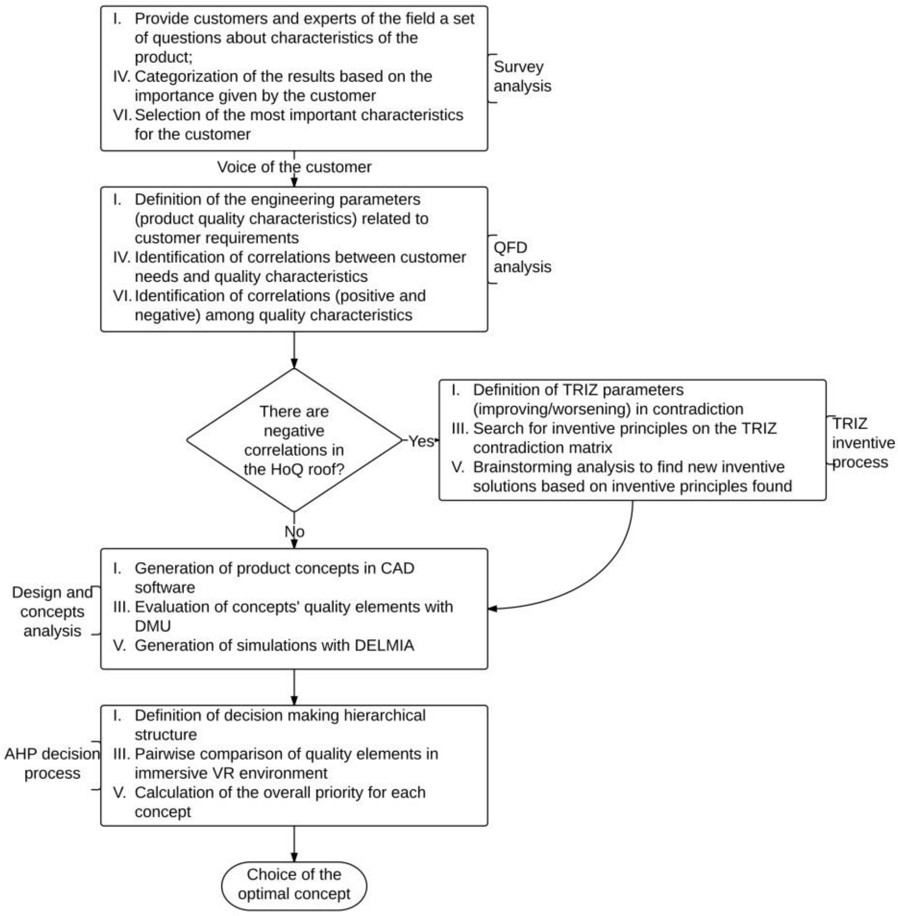

Figure 22. Flowchart of the methodology adopted

Table 11. Most important customer needs

Mean score	Customer need
4.76	Side doors must be suitable for manually loading operations
4.72	Damage to remaining stand trees should be prevented
4.49	Trailer must be dedicated not only to timber transportation, but also to other agricultural and forestry operations
4.46	Lateral rollover is important
4.03	Damage to plants on trailer route should be prevented
4.02	Soil damage by tire effect must be prevented
4.00	Trailer must be suitable for transportation of 1 to 3 meter length of timber

ple, in particular, we used virtual manikins. After the evaluation of product concepts using quality characteristics, a second qualitative evaluation was made by a group of experts that provided their opinion about the importance of each parameter, in order to achieve a quality classification for the product variants. The instrument chosen was AHP (Saaty, 1990).

The entire methodology was aimed to produce an optimal concept that could satisfy customer requirements adopting innovative solutions (Di Gironimo, Lanzotti, & Vanacore, 2006). The identification of the optimal concept concluded the concept design process.

Results

The first step of the study was the identification of a set of needs related to forestry operations involving a tractor-trailer combination. The list of requisites was developed starting from the interview of experts in the field. The topics were the following: driving ability in difficult terrain conditions; reduced damage to the environment; trailer adaptability to different payloads and operations; ergonomic operations. The questionnaire was submitted to a group of 21 people involved in forestry activities, composed of: forest engineers, whose activities are associated by timber harvesting, timber transport and road construction; forest rangers, which control forest area for the prevention of law infringement and the preservation of the environment; forest workers, which are people directly involved in harvesting operations. Every person evaluated a set of 14 sentences choosing their degree of adherence to each statement, using a 5-point scale composed in this way: (1) Strongly Disagree; (2) Disagree; (3) Undecided; (4) Agree; (5) Strongly Agree. A mean score for each sentence was calculated, obtaining a set of requirements with a score greater or equal to 4, reported in Table 11.

After the survey, the House of Quality was used to find quality characteristics to be designed that reflected the customer needs. The completed HoQ is shown in Figure 23.

A set of quality characteristics (or functional requirements) of the product is identified to satisfy these needs and inserted into the top row of the table. These described the product in measurable terms and directly affected customer perceptions. For example, one of the main customer requirements reported in Table 11

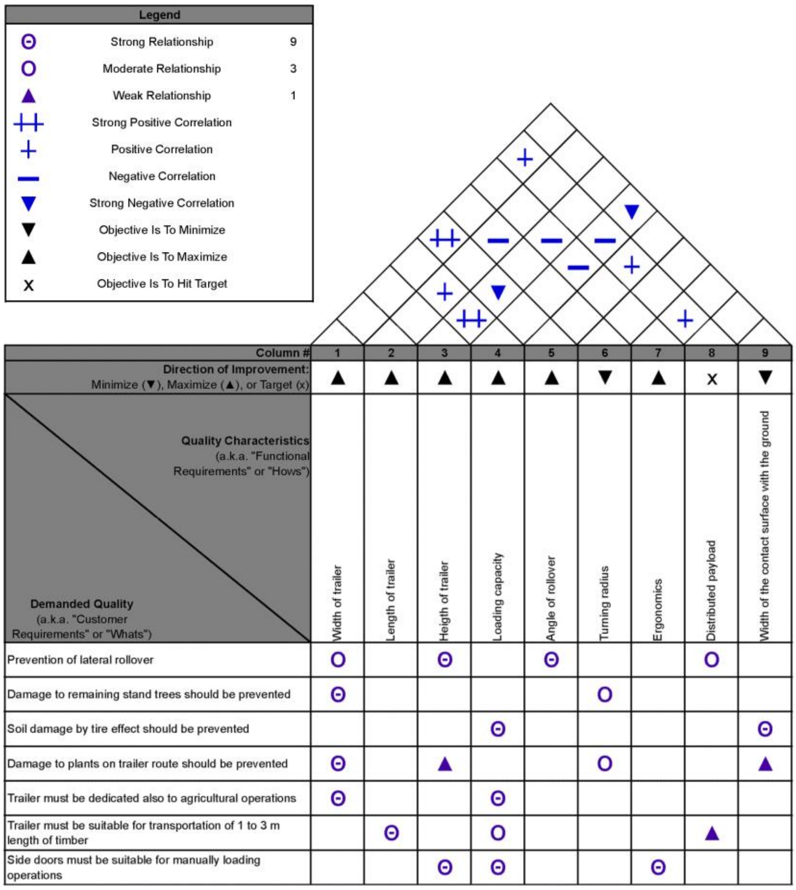

Figure 23. The House of Quality for the trailer design

was "trailer must be dedicated not only to timber transportation, but also to other agricultural and forestry operations".

Once both customer requirements and quality characteristics were identified, we recognized the relations between them reporting the information in the middle matrix of the House of Quality. In the upper part of the House of Quality, also known as the roof, six relationships among quality characteristics were indicated. These relationships can be positive or negative (contradictions). For example, a big height of the trailer is a good solution to prevent accidental impacts with terrain obstacles, but this raises the vertical position of the centre of mass, widening the angle of rollover and posing a threat for dangerous effects. We adopted the TRIZ approach to solve contradictions instead of finding compromises between conflicting quality characteristics. For each conflict, a couple of TRIZ parameters were identified, one worsening and another improving based on the conflicts elements between the engineering characteristics. The intersection between improving and worsening parameters in the contradictions matrix gave the TRIZ inventive principles that we followed in order to find new possible engineering solutions for the product. The use of brainstorming sessions, as well as technical knowledge, was very useful in this phase, because TRIZ analysis works in a high level of abstraction (Terninko et al., 1998).

Table 13 shows the result of the first TRIZ-related step, with the couple of TRIZ improving/worsening performance associated to every conflict between quality characteristics, and the inventive principles chosen to find special solutions. TRIZ elements in the contradiction matrix were chosen regarding of the functions which are in conflict in the system.

For example, in the first conflict, the height of trailer and the angle of rollover were involved. As the ground slope increases, the higher centre of gravity of the load results in lower stability of the vehicle. The performance improved is the length of moving object (3), since the distance of the trailer from the ground is important when the vehicle is moving, and needs to avoid obstacles. The parameter that worsens raising the trailer (and then generating the conflict) is the angle of rollover, associated with the stability (13) principle. The contradiction matrix gave the following inventive principles: segmentation, anti-weight, dynamics, discarding and recovering. The principle selected is dynamics with its sub-principle c: according to it, the solution adopted was making the height of the trailer manually adjustable using a mechanical system that lets the operator change the distance of

Table 12. TRIZ special solutions and technical solutions adopted

No.	TRIZ solution	Technical solution(s) adopted
1	Adjustable height of trailer	Adjustable height of the wheels using a hydraulic system
2	Four wheels (one axle system)	Tandem wheels design
3	Articulated drawbar	Removable drawbar with two joints (tractor and trailer)
4	Symmetrical trailer; turnable trailer	Sliding drawbar or sliding chassis; front drawbar wheel
5	Extendable side doors; chassis tilt system	Extendable supports inside the doors; hydraulic system to tilt the chassis
6	Logs containment system	Adjustable height of logs supports when the chassis is closed; V-shaped chassis

the wheels from the bottom of the trailer when the vehicle is not moving. With this solution, it was possible to increase the maximum terrain slope in which the trailer can be used.

In the second conflict, the loading capacity of the trailer was in contradiction with the width of the ground contact surface. The greater the trailer's weight, the more the pressure that is transmitted to the soil. The vehicle should be adaptable to difficult terrain conditions with a small contact surface with the terrain to minimize the probability of hitting an obstacle. The TRIZ improving parameter was length of moving object (3), while the worsening parameter was weight of moving object (1).The inventive principles found were: anti-weight, dynamics, pneumatics and hydraulics, discarding and recovering. The principle selected was dynamics with its sub-principle b: the solution adopted according to it was a tandem wheels design. The vehicle has two wheels per side, but positioned one behind the other and capable of relative movement to each other (four wheels with one axle system) in order to minimize the contact width and also give great adaptability to different terrain conditions.

Each inventive solution found in the TRIZ analysis (Table 12) was translated in a practical implementation inside the virtual environment. Four concepts were then generated in CAD environment from the combination of various chassis configurations (Figure 24).

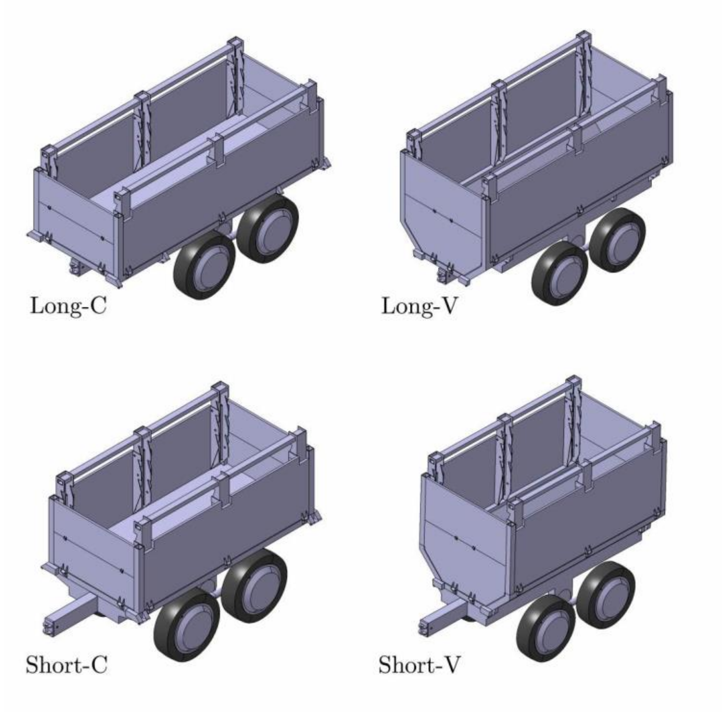

Figure 24. Concepts generated in VR

Table 13. Conflicts translated into TRIZ

No.	Quality characteristic improved	Quality characteristic worsen	TRIZ performance improved	TRIZ performance worsen	Inventive principle chosen
1	Height of trailer	Angle of rollover	(3) Length of moving object	(13) Stability	[15.c] Dynamics
2	Loading capacity	Width of the contact surface with the ground	(3) Length of moving object	(1) Weight of moving object	[15.b], [15.c] Dynamics
3	Turning radius	Length of trailer	(33) Ease of operation	(3) Length of moving object	[1.a] Segmentation
4	Ergonomics	Loading capacity of trailer	(33) Ease of operation	(2) Weight of stationary object	[13.a] The other way round, [25.a] Self-service
5	Height of trailer	Ergonomics	(4) Length of stationary object	(33) Ease of operation	[25.a] Self-service
6	Loading capacity	Distributed payload	(7) Volume of moving object	(13) Stability	[10.b] Preliminary action, [1.c] Segmentation

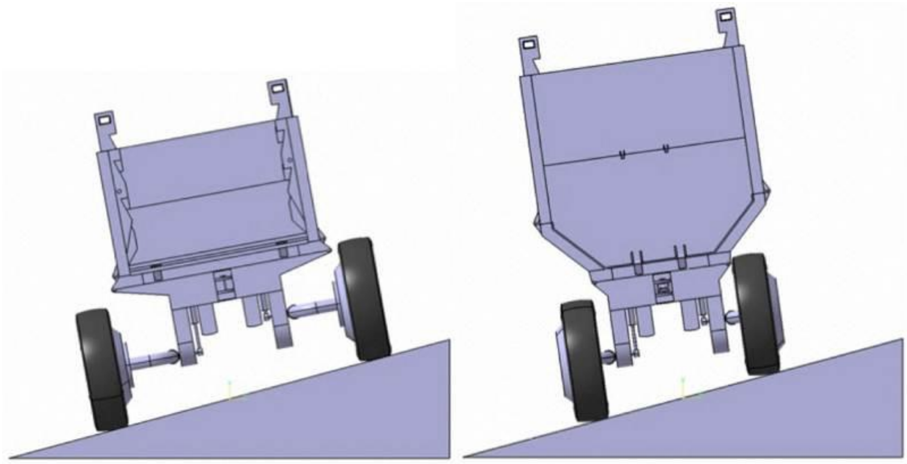

Figure 25. Position of the trailer on sloped terrain with two chassis configurations

The trailers differ in the chassis shape, which has two different configurations: one is C-shaped, the other V-shaped. Moreover, the chassis can be of a short-type or long-type. The difference in the trailer's shape is mainly related to the stability of the vehicle. For example, with the V-shape chassis it is possible to improve the rollover angle without increasing the track width, as showed in Figure 25. The chassis length was chosen mainly in relation to the payload capacity for agricultural use. The concepts were then evaluated based on several quality characteristics illustrated in Table 14.

Table 14. Summary of quality characteristics evaluation

Quality element	**Score**			
	Short-C	Short-V	Long-C	Long-V
Mass [10^3 kg]	2.70	3.14	3.02	3.54
Max payload (logs) [m^3]	2.33	3.93	2.33	3.93
Max payload (chassis filled) [$m^{3]}$	2.68	3.36	4.29	5.38
Angle of rollover [deg]	26.9	28.2	26.3	27.2
Angle of rollover (reversed wheels) [deg]	42.6	38.4	41.9	37.1
Door reachability [% of population]	90	10	90	10
Low Back Analysis [N]	2597	2958	2597	2958

The final evaluation phase of the best concept was carried out, through an interactive design approach, in the Virtual Reality lab of University of Naples Federico II, named "IDEAinVR" (Interactive Design and Ergonomics Simulations in Virtual Reality), Figure 26. It involved the participation of 7 experts in order to give a weight to every quality characteristic and simulations of trailer operations considered in this step, in order to obtain an overall evaluation of each concept. The use of a multi-screen projection system helped the evaluation phase, thanks to the possibility to compare in real time two different solutions.

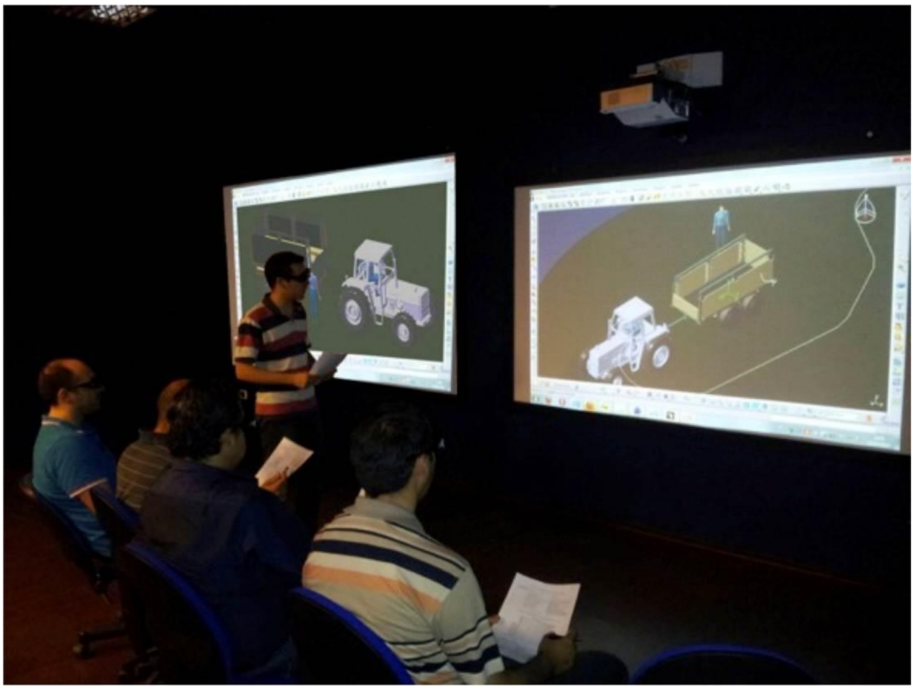

Figure 26. Evaluation phase in the IDEAinVR lab

The instrument chosen for the decision-making process was the Analytical Hierarchy Process (AHP). In the first step of the process, the problem of the trailer's choice was decomposed into several levels, identifying a set of criteria and sub-criteria (Di Gironimo, Matrone, et al., 2013). In the first (top) level there was the overall goal, the trailer's choice. In the second level there were six criteria, which contributed to the goal: mass, loading capacity, angle of rollover, ergonomics, change of trailer's direction, tandem behaviour. The third level was composed of the following sub-criteria: loading capacity (in terms of logs and in terms of the full chassis' volume), angle of rollover (with normal and reversed wheels), and three characteristics related to ergonomics: the reachability of the side door, the Low Back Analysis and the loading operation. In the fourth level (bottom) there were the four trailer candidates. All the criteria and sub-criteria were analysed through the previous step with respect to the four trailers with an objective evaluation, except for the loading operation, the change of the trailer's direction and the tandem behaviour, for which a subjective evaluation by the experts was required. In order to support the decision process, all the evaluation activity was carried out in immersive virtual reality using virtual prototypes and ergonomic simulations prepared in DELMIA, as previously done by Di Gironimo and Patalano (2008) and Lanzotti et al. (2009). Figure 27 shows, as an example, the loading operation simulated using virtual manikins.

Table 15. Final results of AHP evaluation

Criteria (weight)	Sub-criteria	Global weights	Short-C	Short-V	Long-C	Long-V
Mass		0.13	0.20	0.54	0.18	0.08
Loading capacity (0.07)	Loading capacity (logs)	0.07	0.07	0.28	0.11	0.54
	Loading capacity (full chassis)	0.04	0.05	0.10	0.22	0.62
Angle of rollover (0.26)	Normal wheels	0.07	0.15	0.51	0.11	0.22
	Reversed wheels	0.19	0.54	0.14	0.22	0.11
Ergonomics (0.22)	Reachability of the side door	0.04	0.49	0.08	0.36	0.07
	Low Back Analysis	0.08	0.38	0.12	0.38	0.12
	Loading operation	0.09	0.38	0.06	0.44	0.12
Change of trailer's direction		0.11	0.44	0.34	0.13	0.09
Tandem behavior		0.17	0.08	0.37	0.11	0.44
Overall priority			0.34	0.23	0.21	0.22

In Table 15, the final rankings of the alternatives are given against the covering criteria and sub-criteria. To get the final priority of a concept, it was necessary to multiply each ranking by the priority of its criterion or sub-criterion and add the resulting weights for each alternative (Saaty, 2008). The alternative with the highest score was the Short-C trailer, with a weight of 34%. The final concept had a total length of 3.35 m, width of 1.34 m and a height of 1.8 m (door upper limit).

Conclusions

In this study we used a survey to collect a set of requirements in order to identify the most important quality characteristics of the product. For example, the importance of ergonomic operations and the prevention of environmental damage were found to be very important for the customer. Another important requirement was the combined use in forestry and agricultural operations. Many farm tractors can already be adapted for forest use and some of them are purpose made for both farm and forestry application (Russell & Mortimer, 2005), even if these are quite expensive solutions. However, in our approach, managing the conflicts found in the HoQ with TRIZ, several innovative solutions were found. The adjustable height function provides more stability to the vehicle: when the ground slope increases, a lower centre of gravity results in higher stability, in accordance with

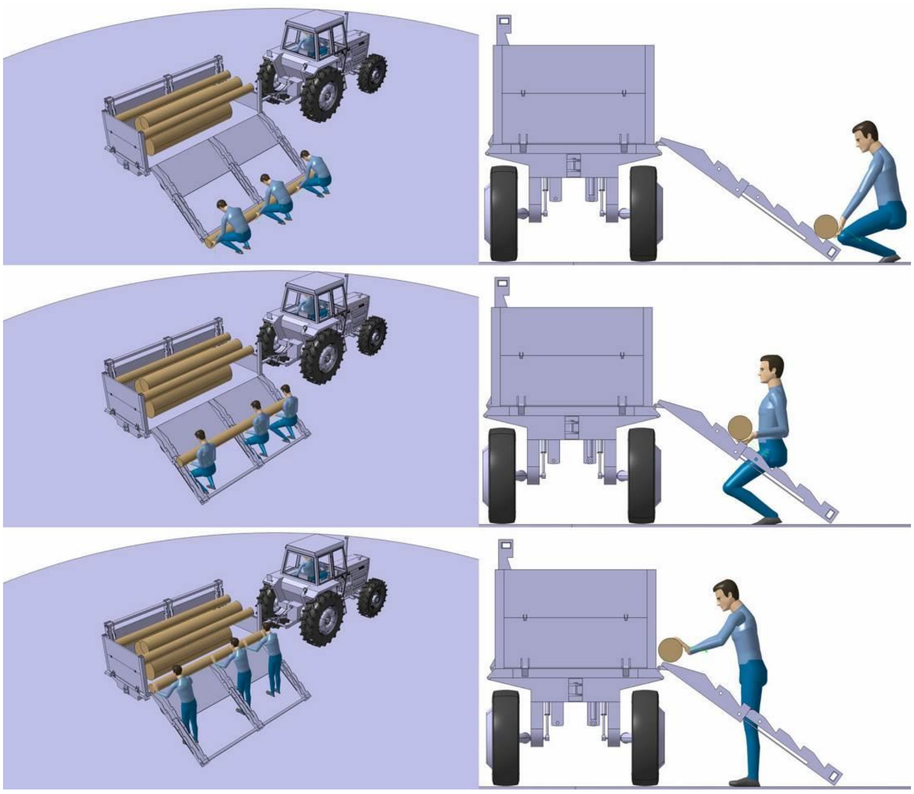

Figure 27. Ergonomic analysis of loading operation

Akay et al. (2004). Moreover, the tandem solution for the wheels reduces soil damage compared with a traditional two wheel, single axle trailer, that causes more ground damage and is affected by rough terrain (Jones, 1996).

The final concept selected, thanks to the combination of a low centre of mass, the tandem design for the wheels and the ability to adopt a reversed wheels configuration, ensures very high stability in conditions of rough terrain and slopes ranging from 30% to 60%, representing a flexible solution for timber harvesting operations in Turkey. The “C” chassis configuration, being lower than the “V” one, ensures more ergonomic loading/unloading operations, because the upper end of the trailer’s side doors is easily reachable by the majority of the population. Furthermore, when the side doors are opened with the loading supports in the extended position, the workers – while pushing the logs inside the chassis – have to support less weight. This is shown by a lower low-back pain evaluation performed on virtual manikins. A trailer with side doors will take less time to unload than one without side doors, and can therefore make more trips per day over a given haulage distance (Hamper & Mason, 1997). Moreover, the Short-C trailer is the smallest between the various alternatives, thus its mass is the lowest. This has a positive effect with respect to the preservation of soil integrity; in fact, a lighter vehicle means less pressure transmitted to the ground by the wheels. On the other hand, the Short-C trailer has a smaller loading capacity with respect to the others solutions. However, this is compatible with its main use in primary transportation activities, where loading volumes are also small. Furthermore, the dimensions of the trailer are in accordance with the Turkish legal standards (Kadayifcilar, 1993). Reduced dimensions are a benefit also with respect to manoeuvrability, in particular in conditions where the density of the stand is high. Forwarders are large vehicles; for this reason they can’t be used in areas where there is a high stand density (Horvat et al., 2005). The tractor-trailer combination designed is able to move inside the forest without colliding with stand trees or plants according to safety recommendations in wood harvesting (Engur, 2011).

The characteristics of the final concept can be summarized as follows. The vehicle is capable of manual loading operations and suitable for rough terrain conditions. In particular, the concept chosen is capable of movement in terrains with slopes ranging from 30% to 60% and with presence of obstacles, providing more productivity among high density stand trees, ergonomic loading operations, and a reduced environmental damage to soil and vegetation. The final concept has a mass of 2700 kg; the payload capacity is about 2.33 m^3 (logs) and the total volume of the chassis is 2.68 m^3; the angle of rollover is 26.9 °; the door is reachable by 90% of the population, and the Low Back Analysis performed for the loading operation showed a maximum value of 2597 N. The final concept chosen is suitable for the Turkish forests, flexible enough for agricultural use and cheap; it can be compared with existent and more expensive trailers dedicated to harvesting operations.

3.2.2 Evaluation of alternative forestry processes for biomass collection in early design stage

Introduction

Many studies forecast a significant increase in the use of energy biomass over the next coming years (Verkerk, Anttila, Eggers, Lindner, & Asikainen, 2011), and the forest industry is already exploring this new growing market. Biomass recovery does add to the complexity of forestry, but it also offers a significant opportunity to increase efficiency, raise value recovery and reduce harvesting and management costs (Windisch, Röser, Sikanen, & Routa, 2013). The recovery of forest biomass generally requires some form of processing – chipping or bundling – aimed at increasing the density and the homogeneity of the feedstock (Spinelli et al., 2012). Such process must be performed as early as possible, in order to accrue its benefit all along the supply chain (Johansson, Liss, Gullberg, & Björheden, 2006). Under ideal access conditions, the biomass can be chipped in the stand, and chips rather than uncomminuted residues can be extracted to the roadside landing (Talbot & Suadicani, 2005). Among other things, direct delivery of chip loads to the roadside reduces landing space requirements, and makes this system most suited to those situations where the forest infrastructure is poor or fragmented (Marchi, Magagnotti, Berretti, Neri, & Spinelli, 2011). In many cases, however, difficult terrain conditions prevent terrain chipping, and the biomass is first extracted to the roadside and then chipped. The situation becomes even more difficult when moving to remote upland areas, which are a main potential source of forest biomass in mountain countries like Italy (Freppaz et al., 2004). Here, the quality of the access network declines rapidly, to the point where no standard truck and trailer convoys can reach the forest landings.

A typical situation for a majority of hillside and mountain operations is that of a landing pad inaccessible to heavy road vehicles, and connected to a proper roadside landing by a low-standard trail, only accessible with tractors, forwarders and light two-axle trucks. Under these conditions, two-stage transport becomes unavoidable, especially if extraction is performed with cable systems, as it often happens in mountain operations. The problem is how to organize the operation so that the overall handling and processing cost is the lowest. This is extremely important, because harvesting and transportation cost can represent approximately 70% of the total biomass cost (Panichelli & Gnansounou, 2008), which represents one of the most important barriers to the increased use of biomass (Rentizelas, Tolis, & Tatsiopoulos, 2009).

In this specific case, the question is a typical point of comminution problem (Björheden, 2008). Should one forward the wood to the roadside landing and chip it there, or is it preferable to chip the wood at the pad with a highly mobile chipper and forward the chips to the landing?

Figure 28. Chipped residue chain: (a) chipping at the yarder pad and (b) dumping the chips at the roadside landing

The answer depends on many factors, including: the distance to be covered, the type of chipper one can take to the pad, the payload that can be moved by the forwarding units with the different products (i.e. uncomminuted wood and chips), the speed that can be reached by the forwarding units, and finally, the interactive delays inherent to each system. The theoretical advantage of chipping at the pad is that chips can make for a heavier payload compared to loose residues, while its disadvantage is that bigger and more productive chippers can be used at the roadside landing. However, this is a theoretical statement, valid only to a point, since one can actually mount an industrial chipper on an all-terrain vehicle and take it to the pad. Besides, this statement falls short of defining a break-even point between reduced payload and increased chipping productivity, which is best determined with the experimental method. Any decision should also account for the potential benefit of chipping directly into the road transport vehicles, which can be accrued only when chipping at the roadside landing. Even in this case, however, the benefit must be proved: if it is true that chipping directly into the trucks can save the additional cost of loading, it is also true that such procedure is a main source of interaction delays, which may cause considerable cost (Spinelli & Visser, 2009). Potentially, discharging the chips on the ground avoids most of the interaction delays (Stampfer & Kanzian, 2006), and the additional time consumption of frequent alignment of the chipper with the transportation unit. Besides, filling the trucks with a loader may be faster, and result in a significant reduction of truck idle time.

Therefore, the goals of this study (Spinelli, Di Gironimo, Esposito, & Magagnotti, 2014) were: (1) to develop a discrete event model for simulating handling and processing cost under varying work conditions, so as to conduct standardized comparisons and sensitivity analyses; and (2) to determine whether and when chipping at the pad is preferable to chipping at a proper roadside landing, accessible to heavy trucks.

Materials and methods

The authors set up an experiment where the same industrial chipper was used alternately for chipping at the yarder pad and at the roadside landing. As in many other mountain operations, the pad and the landing were connected by a steep gravel road, inaccessible to heavy road trucks. The chipper was a drum type, powered by a 250 kW independent engine and was mounted on a two-axle trailer towed by a 130 kW farm tractor, which was used only for relocating the chipper between two adjacent chipping stations. The chipper was fed by a separate 15-tonne self-propelled loader and managed directly by the loader operator through remote control (Figure 28a). When chipping at the pad, the machine discharged directly into 20 m3 trailer bins, towed by farm tractors. Trailer bins were then towed to the roadside landing and their content was dumped on the ground (Figure 28b). During the study, one to three bin trailers were used at the same time, to minimize waiting delays. When chipping at the landing, loose residues were extracted from the pad using a 10-tonne capacity forwarder, which stacked the residues on a large buffer pile (Figure 29a). The chipper worked from the pile and discharged on the ground (Figure 29b). In both cases, chips were later picked up and loaded onto heavy road trucks using a powerful self-propelled loader. Discharging on the ground and reloading trucks is a common technique, which aims at minimizing interaction delays for both the chipper and the trucks. A similar result could be achieved by resorting to roll-on containers or spare trailers, but neither solution is popular among Italian loggers due to the additional cost of purchasing and moving around the additional containers (Spinelli & Hartsough, 2001).

All operators included in the study were experienced professionals, who knew their job and equipment. In order to minimize the effect of different operator adaptation and motivation levels, the study included only operators that were judged to have a high degree of uniformity in motivation and adaptation to the studied machines/systems (Harstela, 1988). All operators had at least 5 years of experience with the type of machine they were using, of which about 2 years with the specific unit object of the study. On the other hand, no attempt was made to normalize individual performances by means of productivity ratings (Scott, 1973), recognizing that all kinds of normalization or corrections can introduce new sources of errors and uncontrolled variation in the data material (Gullberg, 1995). The study site was located on the hills overlooking Florence, at an elevation of about 700 m above-sea-level. The study material consisted of 20 chipper hours, 30 trailer hours (27 trips) and 24 forwarder hours (25 trips). During this time, the operation produced 929 m3 of loose chips, or 263 green tonnes. In order to derive the appropriate production functions, the authors carried out a typical time-motion study, designed to evaluate machine productivity and to identify those variables that are most likely to affect it (Magagnotti & Spinelli, 2012). Each processing cycle was stop watched individually, using Husky Hunter hand-held field computers, running the dedicated Siwork3 time study software (Kofman, 1995). Pro-

Figure 29. Loose residue chain: (a) forwarding loose residue from the yarder pad and (b) chipping them at the roadside landing.

ductive time was separated from delay time (Björheden, 1995), and the production of a biomass load was considered as a cycle, for both forwarding and chipping. All delays were included in the study, and not just the delays below a certain duration threshold, because such practice may misrepresent the incidence of downtime, especially on comparatively long observation periods (Spinelli & Visser, 2008). However, delays generated by the study itself were separated and removed from the dataset.

Output was estimated by counting all the loads produced, and by measuring their individual bulk volumes. Volumes were converted into weights by taking a representative number of loads to a certified weight bridge. Ten 1-kg chip samples were collected from each test, and their moisture content was determined according to the European standard CEN/TS 14774-2. Chip moisture content was 35.4% (standard deviation = 3.9%). At this moisture content, the mean payloads of the forwarder and the chip shuttles were 4.8 and 6.0 tonnes, respectively.

Machine costs were calculated with the harmonized method recently developed within COST Action FP0902 (Ackerman et al., 2014), for an estimated annual utilization of 1600 Scheduled Machine Hours (SMH) and a depreciation period of 8–10 years, depending on machine type. Labour cost was set to 20 Euro SMH^{-1}, inclusive of indirect salary costs. The costs of fuel, insurance, repair and service were obtained directly from the operator. The calculated operational cost was increased by 20% in order to include relocation and administration costs, the former already capable of representing up to 10% of the total machine cost (Väätäinen, Asikainen, Sikanen, & Ala-Fossi, 2006). Costs were calculated separately for the machines in a working state and in an idle state, as when down or being loaded (shuttles). Assumptions and results are shown in Table 16.

Data were statistically analysed to build a DES model capable of representing the operation.

Since 20 years, stochastic simulation has been used to represent forest harvesting chains (Johnson, 1986). Researchers have tried both discrete-event (Aedo-Ortiz, Olsen, & Kellogg, 1997) and dynamic (Visser, McDonagh, Meller, & McDonald, 2004) simulation, but the former seems to have been far more successful (Mobini, Sowlati, & Sokhansanj, 2011; Oinas & Sikanen, 2000). Simulation models in forest harvesting operations aim to improve machine operating methods and interactions between machines, as well as minimize system bottlenecks, thus improving the system as a whole. According to Reisinger, Greene, and McNeel (1988), since the birth of forest harvesting operation simulation, computers have aided in decision-making and improvement of system cost and production factors by balancing equipment within systems and assessing potential advances associated with stand and machine variables. In fact, forest harvesting operation simulation models were launched in the late 1960's as a method of evaluating forest machine concepts (Goulet, Ipp, & Sirois, 1979; McDonagh, 2002). Simulation has been proven as an acceptable method of harvesting operations assessment in a wide range of machine, harvest and stand condition variables (Hartsough, Zhang, & Fight, 2001; Wang & Greene, 1999; Wang & LeDoux, 2003). Eliasson (1999) states that simulation allows the researcher to standardize certain variables so that focus can be directed towards the variable(s) of interest, leading to more robust results.

The simulation was designed to run on Arena 14 software, which is especially suited for supply chain management applications (Abu-Taieh & El Sheikh, 2007). Study data were first organized into an Excel spread sheet. Element time data were then imported into the Arena Input Analyzer distribution-fitting software. Input Analyzer reads the data contained into the text file, builds automatically a histogram representation of the data and tries to fit several statistical distributions. Input Analizer also determines quality of fit by performing both a Chi-square and a Kolmogorov– Smirnov (K–S) test. In this case, we only used the K–S, since the distributions were continuous. Distributions with p values lower than 0.05 were rejected, while distributions with larger p values were accepted. When the test failed, the data was checked for outliers, assuming that these points would be generated by some special causes. A statistics package, Minitab 16, was used to dis-

Table 16. Costing assumptions and machine rates

	Chipper	Chipper	Shuttle	Shuttle	Forwarder	Forwarder
State	Working	Idle	Working	Idle	Working	Idle
Investment (€)	350,000	350,000	100,000	100,000	240,000	240,000
Resale (€)	105,000	105,000	30,000	30,000	72,000	72,000
Service life (years)	10	10	8	8	10	10
Utilization (h year^{-1})	1600	1600	1600	1600	1600	1600
Interest rate (%)	4	4	4	4	4	4
Depreciation (€ year^{-1})	24,500	24,500	8750	8750	16,800	16,800
Interests (€ year^{-1})	9590	9590	2775	2775	6576	6576
Insurance (€ year^{-1})	2500	2500	2500	2500	2500	2500
Repairs (€ year^{-1})	12,250	12,250	4375	4375	8400	8400
Diesel (L h^{-1})	35	0	10	0	13	0
Diesel (€ h^{-1})	46	0	13	0	17	0
Lubricant (€ h^{-1})	5	0	1	0	2	0
Total (€ h^{-1})	81	31	26	12	40	21
Crew (n)	1	1	1	0	1	1
Labor (€ h^{-1})	20	20	20	20	20	20
Overheads (€ h^{-1})	20	10	9	2	12	8
Total rate (€ h^{-1})	121	61	55	14	72	50

Note: Labor cost includes 45% indirect cost.

play the box plot of each dataset in order to identify and remove outliers. Data points exceeding 1.5 times the interquartile range were considered outliers. If the K–S test failed again after correction, then empirical distributions were used. No normal distributions were used in the software model since they could theoretically generate negative values during simulation runs. Even when a normal distribution returned the best fit, other distributions limited to positive values (e.g. Weibull) were used. Table 17 shows the distributions used for the different machines and time elements.

The information coming from the study was used to create a rough flowchart draft of the two alternative chain models, namely: “chipping at the pad” and “chipping at the landing.” Two simulation models were then designed using Arena 14 to obtain the final process maps. In Arena, what flows through the chart is an object called entity. For this particular case study, the entity was designed to be a single load (of uncomminuted sections or chips, depending on the process). Using the single load as the entity reflected the actual structure of the source data and allowed building an intuitive simulation model, which was easier to verify. The process itself was modelled in such a way that each load went through several activities, was affected by delays, and eventually was collected at the landing site.

Both models were verified by comparing the simulated average time per load with the actual data, using the Mann–Whitney–Wilcoxon statistical test. This was made for a first batch of 5000 simulated loads, with the additional purpose of excluding the occurrence off runtime errors. The difference between real and simulated data was 1.49 and 1.97%, respectively for chipping at landing and chipping at the pad.

However, the time study did not last long enough to offer a reliable representation of delay time, which is typically erratic (Spinelli & Visser, 2008). Therefore, delays were modelled based on another database available to the authors, and obtained from a large study of delays in chipping operations (Spinelli & Visser,

Table 17. Distributions used for the model

Point of comminution	Activity	Units	Distribution	Arena expression
Landing	Chipping	Seconds	Exponential	EXPO (431)
	Chipper delays (chance 34%)	Seconds	Lognormal	33 + LOGN (2.08e+003, 6.05e+003)
	Travel unloaded – forwader	m/s	Weibull	1.57 + WEIB (0.472, 3.35)
	Loading – forwarder	Seconds	Triangular	TRIA (285, 490, 550)
	Travel loaded – forwarder	m/s	Triangular	TRIA (1.57, 2.55, 2.75)
	Unloading – forwarder	Seconds	Triangular	TRIA (225, 407, 600)
	Forwarder delays (chance 34%)	Seconds	Gamma	83 + GAMM (1.41e+003, 0.638)
	Discrete events (chance 50%)	Seconds	Exponential	50 + EXPO (745)
Pad	Chipping	Seconds	Uniform	UNIF(670, 1.22e+003)
	Chipper delays (chance 34%)	Seconds	Lognormal	33 + LOGN (2.08e+003, 6.05e+003)
	Park tractor	Seconds	Exponential	120 + EXPO (74.7)
	Travel unloaded – tractor	m/s	Beta	1.73 + 1.62 × BETA (1.24, 1.41)
	Travel loaded – tractor	m/s	Beta	2.14 + 0.39 × BETA (1.33, 1.25)
	Unloading – tractor	Seconds	Empirical	DISC (0, 266.5, 0.3, 286.5, 0.4, 306.5, 0.7, 326.5, 1, 345.5)
	Tractor delays (chance 34%)	Seconds	Gamma	83 + GAMM (1.41e + 003, 0.638)
	Discrete events (chance 50%)	Seconds	Exponential	50 + EXPO (745)

Table 18. Productivity, cost, fuel use, and utilization

Treatment	A	B	C	D
Point of comminution	Landing	Pad	Pad	Pad
Shuttles	1	1	2	3
Chipper productivity (t h^{-1})	10.8^a	13.1^b	11.8^c	11.0^a
System productivity (t h^{-1})	4.7^a	4.8^a	7.3^b	9.8^c
Production cost (€ t^{-1})	25.7^a	27.3^b	22.7^c	22.7^c
Fuel use (L t^{-1})	4.54^a	2.99^b	3.25^c	3.50^d
Chipper utilization (%)	60.4^a	19.8^b	30.5^c	41.1^d
Transport utilization (%)	80.3^a	72.1^b	58.6^c	55.1^d

Note: Different letters in superscript indicate that the differences between the mean values presented on the same row (i.e. the differences between treatments) are statistically significant at the 1% level.

2009). This database contained information for about 500 chipper cycles and as many tractor or forwarder cycles, and it was used to model delay event probability and duration. Delay generation was performed by two separate blocks inside the models, one for personal and operational delays (except for those caused by machine interaction), and the other for mechanical delays. This allowed good statistical representations of all delays in the simulated environment.

Using this new improved model, both chains were simulated for a pad-to-landing distance ranging from 500 to 5000 m, which was varied in 500 m units. This was the actual range of distances available at the study site, which was considered representative of mountain operations in Italy. The forwarding of chips was simulated for a number of shuttles ranging from one to three. Four treatments were compared, and namely: chipping at the landing and chipping at the pad with one, two, and three shuttles. Each combination of distance, shuttle number and chain type was simulated 30 times. Each run was stopped when 250 tonnes of chips had been accumulated at the landing, assuming this quantity as the typical amount of residues produced from the average forest lot in Italy (Spinelli, Magagnotti, & Facchinetti, 2013). The total number of iterations was 1200, corresponding to a mass flow of 303,228 tonnes of chips. Simulated work time amounted to 54,852 hours, for a total expenditure of €7,456,707. Simulated fuel consumption was 1,081,734 L of diesel. Clearly, such a large observation period could only be obtained through simulation. An actual field study of this size would have been far too expensive.

Results

Table 18 shows the main statistics for the treatments on test. Overall system productivity was defined as the total mass output divided the operation residence time (simulated duration). Mean system productivity ranged between 4.7 and 9.8 fresh tonnes per hour. Differences were statistically significant at the 1% level. Overall system productivity grew with machine fleet. It was higher when using two or three chip shuttles, rather than only one chip shuttle or a loose-biomass forwarder.

Excluding interaction delays, the mean productivity of the chipper varied between 11 and 13 fresh tonnes per hour. Mean chipper productivity was higher when the chipper was forced to longer waiting times, as in treatments B and C.

Mean chipper utilization ranged from 20 to 60%. It was highest when chipping at the landing and discharging in a pile on the ground, which removed all waiting for transports. Conversely, mean chipper utilization was lowest for treatment B, when the chipper was forced to wait for the single chip shuttle to reach the landing, dump its load and come back to the pad. Mean transport utilization varied between 55 and 80%, and it was highest for treatment A (chipping at the landing), which enjoyed complete machine independence and was spared all interaction delays. Utilization differences between treatments were all significant to the 1% level. As expected, chipper and transport fleet utilization had an inverse relationship. High chipper utilization was obtained by detaching a large number of transports to serve it, which decreased transport utilization. Using fewer transports increased their utilization (less queuing), but it also decreased chipper utilization.

Mean production cost varied from €23 to 27 per fresh tonne. The full range of variation was between €13 and 47 per tonne (Figure 30). Cost was highest for treatment B, and lowest for treatments C and D. There was no statistically significant difference between the mean costs recorded for these last two treatments. Chipping at the pad and using two or three shuttles for chip extraction was 10% less expensive than chipping at the landing. However, when only one chip shuttle was available, chipping at the pad was 6% more expensive than chipping at the landing.

Fuel use varied between 3 and 4.5 L diesel per tonne of fresh chips. Fuel use was highest for treatment A, chipping at landing. The best compromise between reduced production cost and low fuel use was offered by treatment C, chipping at

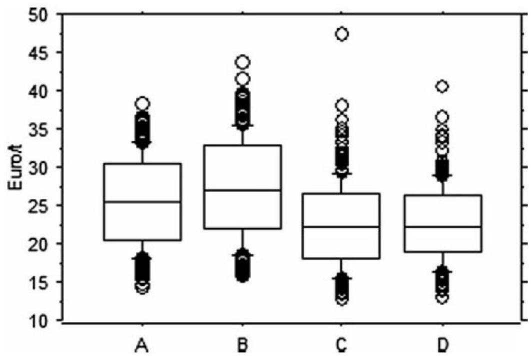

Figure 30. Box-plot for production cost (€ t^{-1})
Note: A = chipping at the roadside landing; B = chipping at the yarder pad (1 shuttle); C = chipping at the yarder pad (2 shuttles); D = chipping at the yarder pad (3 shuttles).

Table 19. ANOVA tables for the effect of treatment and distance

Effect	DF	SS	η^2	F value	p value
Chipper productivity (t h^{-1})					
Treatment	3	219.600	0.04	15.251	<0.0001
Distance	1	0.141	0.00	0.029	0.8639
Interaction	3	2.661	0.00	0.185	0.9068
Residual	1192	5722.128	0.96		
Unit cost (€ t^{-1}) Log-transformed					
Treatment	3	0.134	0.01	28.166	<0.0001
Distance	1	10.238	0.83	6441.577	<0.0001
Interaction	3	0.065	0.01	13.555	<0.0001
Residual	1192	1.895	0.15		
Chipper utilization (%) Arcsine-transformed					
Treatment	3	$2.23E^{-04}$	0.26	286.111	<0.0001
Distance	1	$2.62E^{-04}$	0.30	1007.962	<0.0001
Interaction	3	$7.44E^{-05}$	0.09	95.269	<0.0001
Residual	1192	$3.10E^{-04}$	0.36		
Transport utilization (%)					
Treatment	3	1.870	0.18	171.301	<0.0001
Distance	1	4.371	0.41	1201.027	<0.0001
Interaction	3	0.093	0.01	8.485	<0.0001
Residual	1192	4.338	0.41		

the pad with two shuttles.

Extraction distance and treatment had a significant effect on all performance indicators, except for chipper productivity (Table 19). Extraction distance and treatment impacted system balance, which was upset by the increasing distance and partially restored by adding a new chip shuttle to the system. In general, distance had a stronger effect than treatments, at least within the wide distance range considered in this study. Such effect was particularly strong on overall production cost, whose variability was explained by distance for over 80%. The effect of distance on chipper utilization could be compensated by adding a new shuttle, which explains why this effect was relatively weak in that specific case. The high significance of the interaction factor pointed at the strong relationship between distance and treatment in their effect on system balance, which was the ultimate reason for the different performances of the four treatments.

Figure 31 shows the relationship between production cost, distance, and treatment. Treatment B is the most expensive, along the full range of distances. The productive capacity of a single shuttle is much below the capacity of an industrial chipper, which causes a dramatic loss of productivity and a parallel increase of production cost. Once the balance between chipper and shuttle fleet is restored, chipping at the pad (treatments C and D) proves less expensive than chipping at the landing (treatment A). The difference between treatments C and D is minimal, and changes with distance. Detaching one additional chip shuttle is a discrete step with a fixed unit cost, which is offset as distance increases. In general, the longer the extraction distance, the higher the benefit derived from a larger transport fleet, and from the higher payload capacity achieved when hauling chips rather than loose residues.

Fuel use is highest when extracting loose residues and chipping them at the roadside landing. Fuel use is lowest when chipping at the pad and hauling the chips with a single shuttle, but this solution incurs the highest production cost. The best combination is offered by treatment C, where chips are processed at the pad and hauled with two chip shuttles. This solution offers both low fuel consumption and low production cost.

Conclusions

Simulated chipper productivity matches quite well the figures obtained from previous studies of similar machines under similar conditions (Spinelli & Hartsough, 2001). The same is true for chipper utilization (Spinelli & Visser, 2009). The significantly higher productivity recorded for chipping at the pad as compared to chipping at the landing finds several possible explanations. First, piles built at a landing were bigger, taller and more entangled, which slowed down feeding. Second, the chipper working at the pad experienced variable amounts of waiting delay, during which the loader could rearrange the piles, so as to make feeding faster, once the next chip shuttle showed up. Corroboration of individual productivity and utilization figures reinforces confidence in the general reliability of our model, which goes beyond the analysis of single work steps and tries to mirror a whole chain that starts with uncomminuted biomass at a yarder pad and ends with chips at the roadside landing.

Our model can represent the varying interaction of chipper and chip shuttles under changing work conditions. It also separately estimates work time and delay time,

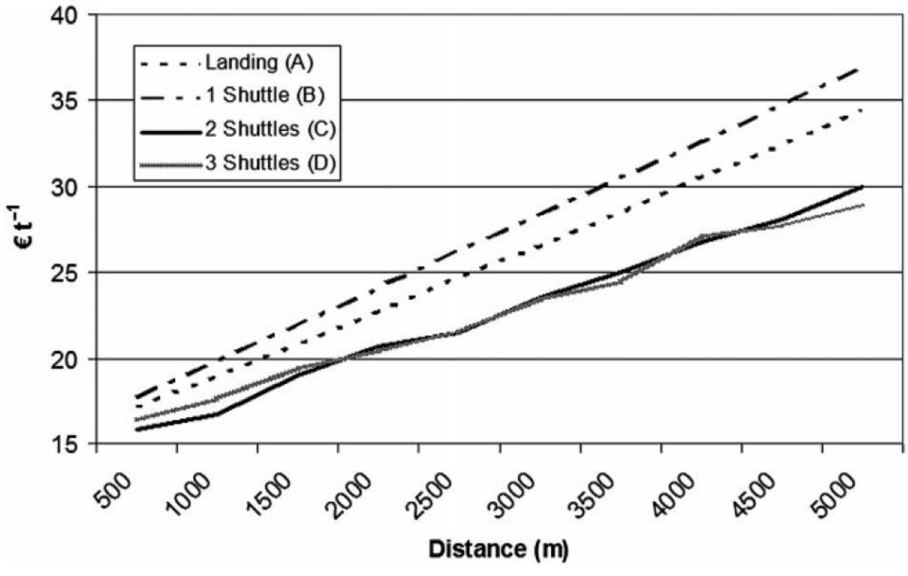

Figure 31. Relationship between production cost, extraction distance, and treatment

allowing the association of each machine state with a specific cost. In the idle state, a machine will use no fuel, and therefore, models that apply the same cost for work and delay time are less accurate in their cost estimates.

What is more, our stochastic model represents uncertainty much better than any deterministic model, which may assist risk-averse operators to assess the probability of occurrence of each cost range for any of the tested options and distances. For instance, assuming an extraction distance of 2500 m there is a 68% chance that production cost will range between €23 and 26 per fresh tonne when chipping at the landing, and between €19 and 24 per fresh tonne when chipping at the pad with a support fleet of two chip shuttles. Knowing the field of variation of projected costs, entrepreneurs will be best equipped to make their decisions about accepting any given job or price.

In this respect, it is important to notice that the cheapest option also presents the largest field of variation. That is the obvious result of the additional uncertainty introduced by interaction delays, which are practically absent in the more expensive option represented by chipping at landing. Under these circumstances, a decision maker can opt for the system offering lower supply cost but higher uncertainty, or for the more expensive system that offers a more predictable result. The final decision will depend on the fine balance between risk-aversion and cost reduction. In this respect, readers must remember that the better performance of chipping at the pad with two or three chip shuttles depends on the higher payload and speed of chip shuttles compared to loose-residue forwarders, and on the possibility to use one driver for two shuttles. If these conditions are not realized, then the result might be very different. Introducing an enlarged space forwarder capable of carrying a larger payload may tilt the scales in favour of chipping at landing. The same could occur if all chip shuttles were run by their individual drivers, whose wages would represent a net cost when idled during container loading. We have not tested these specific cases because we did not have the base data to simulate them, but readers must be aware that the numbers generated by our model are only valid for the specific assumptions used to build it. In contrast, the modelling technique itself can be used to simulate a larger variety of conditions once the base data for modelling these conditions are made available.

In our case, the higher speed and payload of the chip shuttles are decisive factors. When chipping at the landing, utilization is highest for both the transport and the chipper, but that is not enough to tilt the scales. Used for hauling loose residues, the forwarder is not productive enough, at least not in its current standard configuration. The gap between the two alternative chains grows with distance, which demonstrates that transportation is the weak link.

In any case, distance is by far the most important factor in determining supply cost, since it accounts for 80% of the variability in the data. That is no wonder, given the very wide range of distances explored in our simulation. The maximum value in the distance range is ten times larger than the minimum value, which explains the strong effect of distance as an independent variable. More distance means more work, regardless of how the work is organized. Both main chains are rationally organized and their performance cannot differ as much as to overcome the effect of such a large distance variation. In fact, if any of the two chains was clearly superior to the other, there would be no need to use sophisticated simulation techniques to demonstrate its superiority.

Both chains are sensitive to system balance. When chipping at the landing, system balance can be obtained either by commissioning more forwarders to assist the same chipper, or by getting the same forwarder to work longer hours than the chipper. When chipping at the pad, system balance admits one solution only: commissioning an increasing number of shuttles as distance gets longer. In both cases, distance is the factor upsetting system balance, which can be restored by manipulating the number or the schedules of the transport units.

Our simulation was based on the assumption that the buffers were large enough to avoid interaction with cable yarding and road transportation. The yarder pad was accessed after the yarder had been removed, while the roadside landing offered enough space that all units could work simultaneously without interfering with each other: for example, the chipper or the chip shuttles could keep discharging into the chip pile, while a truck was being loaded from it. Operational planning should always include the selection of a roadside landing offering enough space for smooth operation.

Finally, some practicalities that have a strong impact on chain viability. It goes without saying that chipping at the landing is only viable if a proper roadside landing is available. If not, this could be built, but building cost should be added to the calculation. In contrast, chipping at the pad is an option only if the track leading from the pad to the landing allows for exchanging of incoming and outgoing chip shuttles. Otherwise one is forced to use one chip shuttle only, which is the most expensive solution and should always be avoided. If the extraction route intersects or includes a public road, then chipping at the pad is preferable because chip loads are contained, whereas loose residues make up for bulky loads, and the convoy is often too tall and/or wide for circulation on public roads, unless the biomass has been previously bundled (Spinelli & Magagnotti, 2009).The simulation model built within the scope of our study can assist supply chain managers when checking the profitability of an operation, or when assessing the competitiveness of alternative options. The model returns mean supply cost and supply cost variation as a function of extraction distance, operation type, and number of chip shuttles. Costing assumptions can be changed in order to gauge the sensitivity of supply cost to such factors as diesel fuel price, usage intensity and depreciation schedules, among others. For any given set of working conditions, the model can point at the cheapest and safest supply system. In the specific case considered by our simulation, chipping at the pad with a chipper and two shuttles is the best compromise solution of low supply cost and fuel consumption. Fuel savings could be maximized by reducing the transport fleet to one shuttle, but that would also maximize cost. In contrast, chipping at the landing would incur a higher cost and fuel consumption than chipping at the pad.

3.2.3 Concept design and virtual prototyping of an innovative skidding winch using a DES-TRIZ approach

Introduction

The main objective of this work (Di Gironimo, Balsamo, Esposito, Lanzotti, & Melemez, 2014) was to design an innovative skidding winch aimed to improve timber harvesting productivity, operators' safety, and reduce environmental damage in contexts in which mechanized harvesting is limited. The selected study area was the north-western Black Sea region of Turkey. In the proposed methodology, the harvesting process was simulated with Discrete Event Simulation (DES) software in order to identify bottlenecks. An alternative process was compared with the original one within the DES software itself in order to validate further steps oriented to generate new innovative product concepts. The development of the product was focused towards customer satisfaction, collecting customer requirements and identifying quality characteristics with a QFD approach. Contradictions identified in the design phase were solved using the TRIZ contradiction toolkit, generating different product concepts. Inventive solutions provided by TRIZ were designed within parametric CAD software. The concepts were compared in virtual environment with focus on ergonomics, selecting an optimal solution. The results showed that with the concept adopted is possible to achieve a substantial increase in productivity, ranging from 121% to 133%, in terms of kilograms of logs per hour deposited on the landing. Moreover, the final concept allows for ergonomic loading operations and reduces environmental damage to soil and vegetation.

Materials and methods

The methodology we adopted in this study is focused in its initial phase to the identification of bottlenecks in the process with a simulation step that involves also the comparison with an alternative system. We collected several demanded product characteristics via a survey administered to a group of 30 expert people involved in forestry activities, consisting of forest rangers, technical staff and forest workers. Then, we used the House of Quality, in association with TRIZ toolkit, to identify engineering solutions and solve contradictions. We designed several product concepts with the help of CAD software, and the concepts were evaluated in virtual environment with respect to ergonomics.

More in detail, the simulation of the real harvesting process that was adopted in the study area was carried out with Discrete Event Simulation (DES) software. The actual system was modelled and simulated within the software Arena 14, followed by a simulation of an alternative process in which the skidder was equipped with a trailer. The conceptual design of the skidding winch was developed following the methodology proposed by Melemez et al. (2013). To obtain information from the customer about the main product's demanded quality characteristics, we used a Likert survey (Bertram, 2009). We adopted the House of Quality (HoQ) (Hauser & Clausing, 1988) to find product characteristics that reflected the customer needs. To solve inventive problems observed in the previous step, we took advantage of the TRIZ approach (Gadd, 2011). We designed product concepts with the CAD software CATIA V5, performing a quantitative evaluation with DMU and ergonomic tools (Di Gironimo, Patalano, et al., 2009). The interaction with workers was evaluated using manikins in virtual environment, exploiting methods adopted in previous studies (Di Gironimo, Lanzotti, et al., 2012; Di Gironimo, Pelliccia, et al., 2012).

Time measurements in the area were conducted during timber harvesting practices. We chose the compartment 10A (harvesting unit) of Devrek Forest District Directorate for data collection. This compartment was harvested in accordance with the forest management plan over April to June 2011. The compartment has typical land characteristics of the region and is suitable for implementation of various extraction methods. The average slope of the compartment is about 30%, ranging from 20% to 40%. The stand type is a mixture of beech (*Fagus orientalis* – Lipsky) and oak (*Quercus spp.*). The average skidding distance considered in this study was 100 m for all extraction methods. Timber was skidded uphill except for skidding with animal power on skid trails. The logs used in the study were chosen in the range from 20 to 50 cm in diameter, and from 1.5 m to 4 m in length. The volume of logs was calculated according to Huber's formula. We recorded the diameters and lengths of the transported logs and calculated their volumes. The time of each working phase moving the trees from the stump to the roadside was measured and manually recorded on prepared forms. These forms were arranged separately for each skidding method. In addition, skidding or hauling distance, slope, and the direction of skidding were measured and recorded on the recording forms (Melemez, Tunay, & Emir, 2014).

The analysed process was essentially divided into three sub-processes:

1. Cut to length: the trees are felled and divided into logs;
2. Pulling/Winching: under conditions of steep terrain, logs are hooked and pulled to a position where the soil is less steep using an electric winch equipped on the tractor;
3. Skidding: the logs, now located on a flat terrain, are partially lifted from one end and dragged up to a landing where they are unloaded using a skidding winch that is equipped with a blade at its base.

Starting from the information collected from current real system, a rough flowchart draft of the process was created. A simulation model was then designed using Arena 14 to obtain the final process map. In Arena, what flows through the chart is an object called entity (Kelton, Sadowski, & Zupick, 2009). For this particular case study, the entity was designed to be a single load skidded from pad to landing. The process itself was modelled in order that each load goes through several activities (e.g. is loaded or transferred), is affected by delays, and eventually is collected at the landing site. In accordance with DES, the macro-operations of the process were divided into elementary operations, and for each of them we defined a start and end instant. Data were captured from time study forms into the spreadsheet software Microsoft Excel. The data were copied and pasted into text files, from which they could be imported into Input Analyzer, the distribution-fitting software compatible with Arena 14. We used Input Analyzer to fit the most appropriate theoretical distribution to each data set. These distributions were tested in terms of how well they described the data, using the Kolmogorov-Smirnov (K-S) test. Distributions with a P-value of less than 0.05 were rejected, while distributions with a P-value greater than 0.05 were not rejected (in this particular case, we used empirical distributions generated from the real data). No normal distributions were used to fit theoretical distributions to empirical data, even if they had higher P-values than any of the other distribution options. The reason for this is that a normal distribution can result in the return of negative values during simulation runs from the function's tail (Kelton et al., 2009). Negative observations would be unrealistic in this situation, considering that all real world observations were positive measurements. With regard to the two travel operations modelled, "Travel empty" and "Travel load", the speed of transports (and their relative distributions) was obtained from recorded times and route distances. In this way it was possible to carry out sensitivity analyses aimed to see how the system reacted to a change in the distances covered. Ground slope affects travel speed: when the terrain is steep, the vehicle travels with lower speed. The speed is reduced also by the load weight, especially in steep uphill trails. Load variables important in skidding include weight, number of logs grappled or number of trees hooked (Akay et al., 2004). To simplify the model, a constant load of 800 kg was considered for each run; 30 replications, each of 8 hours, were simulated in the software. For each replication, five different distances were simulated: 50 m, 100 m, 150 m, 200 m and 250 m.

We used the simulation to confirm that the system had a queue on the operation of "Travel empty". This meant that the skidding operation was a bottleneck for the whole process. Then, we modelled a different extraction technique; in particular, a process in which a skidder and a trailer were used in a combined way. The main constraint of this alternative solution was that the trailer is able to connect directly to the skidder. This system was compatible with a forwarding process, because in the actual process after bringing the logs on the pad (from a very steep slope that required the use of a skidding winch for the operation of pulling), they were transported across a forest road suitable for a tractor and a trailer. Since the two alternative systems shared the same initial and final steps (felling and pulling), both systems were modelled with respect to the transport of logs from the landing to pad. A constant load of 6000 kg was assumed in the alternative system, thanks to the much bigger load capacity of the trailer rather than the skidding winch. Sta-

Table 20. Demanded quality elements

No.	Demanded quality
1	Back rollover prevention
2	Lateral rollover prevention
3	Back tires protection
4	Damage to remaining stand trees and plants must be prevented
5	Soil damage must be prevented
6	Capability to pull in high density stand
7	Capability to pull in high slope conditions
8	Prevent cable break
9	Ease of loading operation
10	High productivity

tistics used to model the forwarding operation were based on a previous study (Spinelli & Visser, 2009). This study contained information of about 500 chipper cycles and as many forwarder cycles, and it was adopted also to model delays. We considered our process compatible with this time study, since forwarding operations were performed using a tractor-trailer combination and ground conditions were similar to those of our study area. The elementary steps of the forwarding operation modelled in Arena were: travel empty; manoeuvre; load; travel loaded; unload. Moreover, discrete events (rest, planning, other work) and delays (breakdown, other delays) were included in the model, following the same approach of Spinelli et al. (2014). As previously described for the data coming from the original time study, the times related to forwarding were imported in Input Analyzer to fit several statistical distributions before the implementation in Arena 14. We calculated productivity, in terms of kilograms of logs per hour deposited on the landing, for each distance and for both systems.

After the DES phase, which demonstrated the convenience of adopting a combined skidding/forwarding process, we developed new skidding winch equipment. To focus the design toward customer satisfaction, we obtained information from the customer about the desired product’s characteristics, preparing a survey. In particular, we adopted a 5-point Likert scale because it gives a good granularity to the choice range and an “indifferent” option (Bertram, 2009). The “questions” were formulated as statements, to which people could answer selecting one of the following options that represent the degree of adherence to the statement: strongly disagree (1), disagree (2), undecided (3), agree (4) and strongly agree (5). The aim of the questionnaire was to collect the voice of the customer providing an input to the House of Quality. Several different needs were identified and proposed to people involved in forestry operations to obtain the classification from the survey. We started focusing on the following general needs: tractor stability, prevention of cable breaks, preservation of environment, improvement of productivity and ergonomic operations. A set of demanded quality elements was then identified in several statements (Table 20). Statements 1 and 2 concerned the possibility of vehicle’s rollover. Lateral and back rollovers were taken separately into account since the risk for them to occur was different, although the negative effects were similar. Since the steeper the terrain, the higher the risk of rollover, the skidder-blade had to be designed in order to minimize the risk of such an accident. Statement 3 concerned the importance of protecting the back tires from a possible impact with the logs that were pulled. The damage to little plants and other vegetation was taken into account in statement 4: damaging plants and growing trees can pose a serious risk to the environment, and compromise future productivity. Statement 5 took into account the damage of the soil by the movement of the vehicle into the forest. Statements 6 and 7 described working conditions in Turkish forests, which are characterized by steep terrain and dense and irregular plantation. Statement 8, related to cable break, concerned one of the main causes that lead to the interruption of work. Statement 9 was taken into account because in small-scale harvesting many operations are still done manually, like hooking and lifting the logs. There is the need to ensure that such operations satisfy ergonomic criteria and could be performed by the largest amount of population possible. Statement 10 concerned productivity, which was one of the key aspects to evaluate the efficiency and profitability of a process.

We administered the survey to a group of 30 expert people involved in forestry activities, consisting of forest rangers, technical staff and forest workers. Forest rangers are governmental persons that research and control forest area, working on field for the prevention of law infringement and the preservation of the environment. The technical staff was composed by forest engineers, governmental persons whose job include the management and administration activities necessary to transfer the standing tree into a product that is suitable to further processing or woodworking. Forest engineers' activities are associated by timber harvesting, timber transport and road construction. Forest workers are the people directly involved in harvesting operations. They drive vehicles into the forest area, cut, hook and pull the trees and finally skid the logs onto the roadside.

After the survey, we adopted the House of Quality (HoQ) to find product characteristics that reflected the customer needs previously identified. Figure 32 shows the complete House of Quality. Customer Requirements identified using the survey (Table 20) were inserted into the left column of the House of Quality, in the section dedicated to the voice of the customer (Demanded Quality). A set of Quality Characteristics of the product was identified to satisfy these needs and inserted into the top row of the table.

These parameters describe the product in measurable terms and directly affect customer perceptions. Each parameter was also associated with a direction of improvement, indicated with a downward arrow if the parameter was to be minimized, and an upward arrow when the parameter was to be maximized; we used the “x” when the parameter had a particular target value or performance. Once both customer requirements and quality characteristics were added, the associations between both of them were identified and illustrated in the middle matrix of the House (relationships matrix). Every customer need can have a strong, moderate or weak relationship with each quality characteristics, and hence must be satisfied by one or more characteristics of the product.

This is a description of all the quality characteristics identified:

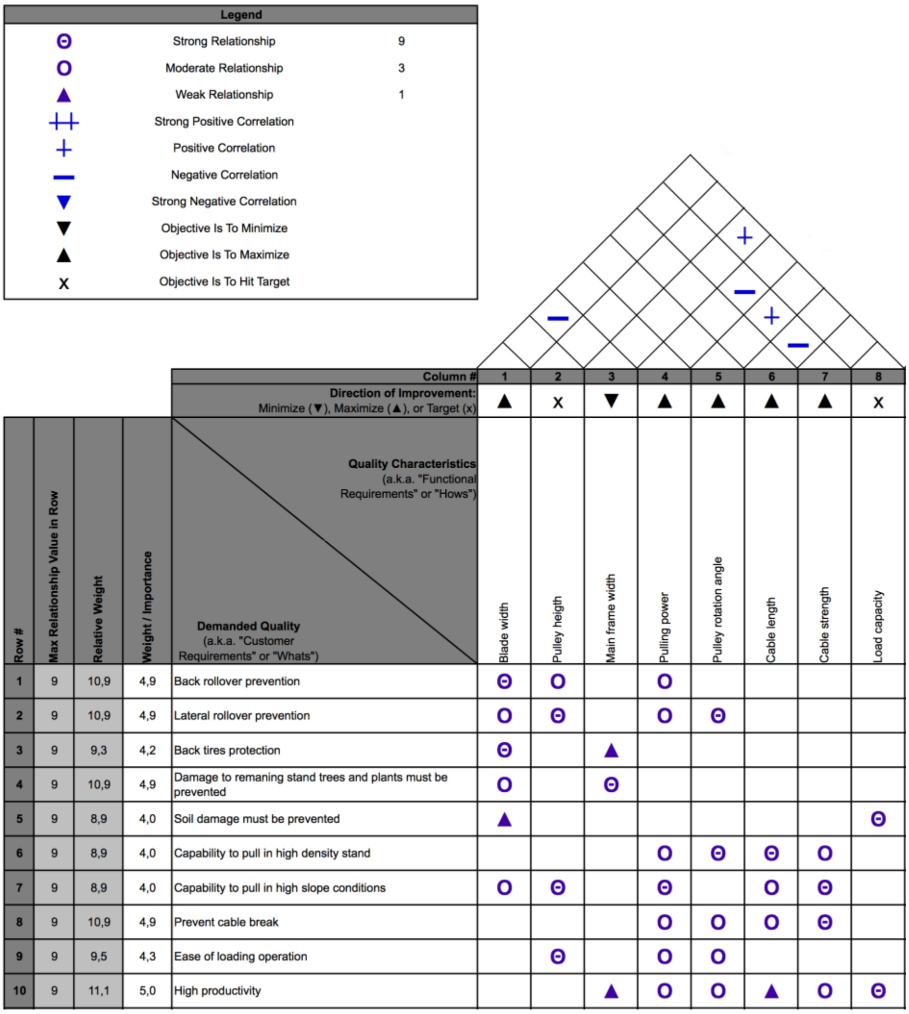

Figure 32. The House of Quality for the skidding winch equipment

1. Larger blade widths have positive effects to back and lateral rollover prevention, back tires protection, damage of the environment and to the capability to pull in high slope conditions. However, big blades cause more damage to the environment (damage to soil and stand trees);
2. The pulley height is related to back and lateral rollover, to the capability to pull in high slope conditions, and to the ease of loading operation. A pulley positioned at the bottom increases the angle of rollover improving the stability of the tractor, but in order to facilitate the operations of the worker is preferable a pulley positioned at the top;
3. The frame width is strongly related to the damage to remaining stand trees and plants. A small main frame is desirable;
4. Pulling power is related to the rollover, to the capability to pull in high-density stand and steep conditions, to the cable break, to the ease of loading operation and to the productivity. Higher power is better;
5. The pulley rotation angle is related to the lateral rollover, to the capability to pull in high-density stand, to the prevention of cable breaks, to the ease of loading operation and to the productivity. A larger angle is desirable to have a greater flexibility;
6. The cable length is related especially to the capability to pull in high-density stand. With a long cable is possible to pull logs that are difficult to reach through linear paths;
7. Cable strength is related to the capability to pull in high slope conditions, to cable breaks and to productivity. A stronger cable allows the possibility to pull together several logs, without cable breaks;
8. Load capacity is related to soil damage and productivity. We would like to increase the load capacity to increase productivity, but this would also result in an increase of the soil damage.

The House of Quality gave the opportunity to identify contradictions between engineering parameters (Hauser & Clausing, 1988), but it didn't give instruments to solve them, with the exception of making prioritization, in order to perform trade-off selections. We identified the following conflicts in the roof of the House:

- Blade width vs. Frame width: a big blade is a good solution to improve the tractor stability to prevent the rollover, but this increases the maximum width of the vehicle resulting increase of the damage to remaining stand trees;
- Pulling power vs. Cable strength: a great power is useful to pull the logs under conditions of high gradients and to increase productivity pulling more logs simultaneously, but it affects the resistance of the cable, increasing the cable breaks when a single cable is used;
- Cable length vs. Cable strength: a long cable allows reaching distant logs and ensures the possibility to bypass obstacles, but also the cable resistance is reduced.

Table 21. Solution of conflicts between quality characteristics

Conflict number	1	2	3
Quality characteristic improved	Blade width	Pulling power	Cable length
Quality characteristic worsen	Main frame width	Cable strength	Cable strength
TRIZ parameter improved	Area of stationary object (6)	Power (21)	Durability of moving object (15)
TRIZ parameter worsen	Object generated harmful factors (31)	Durability of moving object (15)	Stress or pressure (11)
Inventive principle chosen	1: Segmentation	35: Parameter Change	3: Local Quality
Solution adopted	Modular blade	Double-drum system	Protection for the cable

In the House of Quality we identified two types of contradictions that we solved using the TRIZ approach:

1. In the roof matrix, the contradictions between engineering parameters (we identified those contradictions in the upper part of the House of Quality): this type of contradiction was solved with the 40 TRIZ Inventive Principles and the Matrix of Contradictions (Domb, Miller, & MacGran, 1998; Gadd, 2011; Terninko et al., 1998);
2. In each column of the Quality Characteristics section, the contradictions related to functional requirements that are mutually exclusive between two opposite states (points 1, 2 and 8 in the previous list): these are called physical contradictions. We solved physical contradiction with the principles of separation: separation in space, separation in time, separation between the whole and its parts (scale), and separation under condition (Gadd, 2011; Terninko et al., 1998).

To use TRIZ to solve contradictions among quality elements, it was necessary to detect the relative TRIZ parameters based on the conflicts elements between the engineering characteristics. The intersection between improving and worsening parameters in the contradictions matrix gave the TRIZ inventive principles to follow to find new possible engineering solutions for the product. The use of brainstorming sessions and technical knowledge was very useful in this phase, because TRIZ analysis works in a high level of abstraction (Terninko et al., 1998). Table 21 shows the engineering parameters in conflict, the relative TRIZ parameters, the inventive principles chosen and the solutions adopted. In the first conflict the blade width and the frame width were involved. The improving parameter was "area of stationary object" (6): the surface formed by the blade. The worsening parameter was "object generated harmful factors" (31): the maximum size of the skidding winch damages remaining stand trees. The contradiction matrix gave the following inventive principles: "blessing in disguise"; "segmentation"; "composite materials". The principle chosen was "segmentation". The blade was divided into a fixed part and two additional parts. In the second conflict, the pulling power and the cable strength were involved. The improving parameter was "power" (21). The worsening parameter was "durability of moving object" (15). Drum power affects the useful life of the cable. The contradiction matrix gave the following inventive principles: "periodic action"; "parameter changes"; "preliminary action" and "strong oxidants". The principle chosen was "parameter change". We changed the degree of flexibility of the system using a double drum system, so that the stress generated during the pulling operation can be distributed on two cables. Both pulleys, and related drums, were positioned at the centre of the skidding winch to allow their use without affecting the stability of the tractor. In the third conflict the cable length and the cable strength were involved. The improving parameter was "durability of moving object" (15). The worsening parameter was "stress or pressure" (11). The contradiction matrix gave the following inventive principles: "periodic action"; "local quality"; "cheap short-living objects". The principle chosen was "local quality". A protection for the cable was introduced to prevent cable breaks. Another proper "local quality" solution could have been a swaged steel cable, which offers higher tensile strength for the same diameter.

Physical contradictions were all solved using the principle of separation in time:

- The blade width contradiction was solved with the modular blade solution generated in the previous step, since the adoption of additional parts lets the blade being wider when the vehicle is pulling and narrower during the skidding operation;
- The pulley height contradiction was solved introducing a second position for the pulley in the bottom of the skidding winch, which is a solution already adopted on many commercial forestry winches;
- The load capacity contradiction was solved adding a tow bar on the main frame of the skidding winch in order to attach a trailer for the operations of transport. In this way the skidding operation can be replaced with a forwarding operation, loading on the trailer the logs after the pulling operation.

To design the TRIZ inventive solutions, three concepts were generated within the CAD software CATIA V5. We chose CATIA because it supports the entire design process covering all phases of the development of a product, in particular: the design of parts and assemblies (Part Design module and Assembly Design module), the analysis of kinematics and interferences between parts (DMU Kinematics module) and the analysis of ergonomics (Ergonomics Design & Analysis module). We designed product concepts using a top-down modelling approach (Melemez et al., 2013).

All the concepts that were designed share these solutions:

- A double-drum system consisting of two pulleys aligned one above the other in the centreline of the main frame, in order to enhance stability;

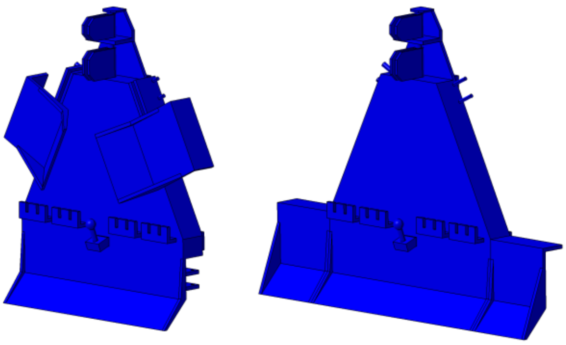

Figure 33. Removable extensions (concept 1)

- A second position for the pulley, with the introduction of a permanent support on the frame, which protrudes from the lower part of the main frame, in order to have the possibility to carry out the pulling operation from two different heights;
- A tow bar, proposed with the introduction of the support above-mentioned, in order to have the possibility to connect a trailer and transform the skidder into a forwarder.

What differentiates the three concepts is the different way the blade of the skidding winch can be widened adding additional parts. We designed three alternatives:

1. The first concept was equipped with totally removable extensions of blade (Figure 33). The main frame had cylindrical supports to store the additional parts when these are not used and other supports on the lower part to mount the additional parts when it is required. The advantage of this system is that it's unnecessary to bring the additional parts when there is no need. A disadvantage is that the parts occupy some volume when stored in their supports on the upper side of the frame, increasing the equipment size.
2. The second concept had rotating additional blades (Figure 34). The additional parts were connected to the main frame by hinges situated down on the backside. This system makes it possible to store the additional parts in the back of the main frame when they are not required, while, when they are in use, they can be rotated and positioned laterally. The advantage of this second proposal is that the additional blades disappear behind the skidding winch when they are not used. A disadvantage is that to extract the additional parts a minimum space is required to guarantee that the blades don't collide with the back tires of the tractor. This limit has the consequence of increasing the distance between the skidding winch and the back of the tractor.

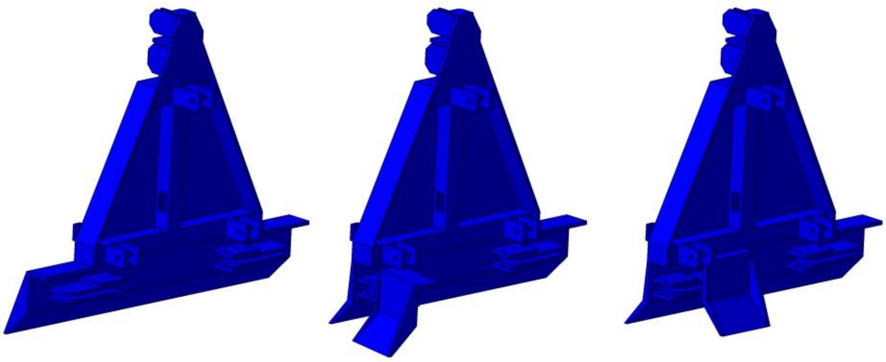

Figure 34. Rotating extensions (concept 2)

3. Additional extractable blades characterized the third concept (Figure 35). The additional blades slide in a sub frame situated in the lower part of the skidding winch; in this way they totally disappear in the equipment's main frame. This system guarantees that the additional blades don't occupy more space when they are stored. Moreover there is no need of a greater distance from the back tires, as seen in the previous solution. A disadvantage of this concept is that it requires the presence of a sub frame, a more complex structure than the previous ones.

Once CAD models of the concepts were designed, we made a quantitative evaluation using digital mock-up (DMU) and ergonomic CAD tools (Di Gironimo, Patalano, et al., 2009). We tested the human response to the product before its creation, using digital human models. This type of simulation allows to evaluate posture, comfort, visibility and accessibility by users of different stature (Di Gironimo, Di Martino, et al., 2012). CATIA V5 allowed the integration of virtual manikins in the CAD 3D environment. For every concept previously designed we prepared a simulation session in which, using the CATIA's Human Builder mod-

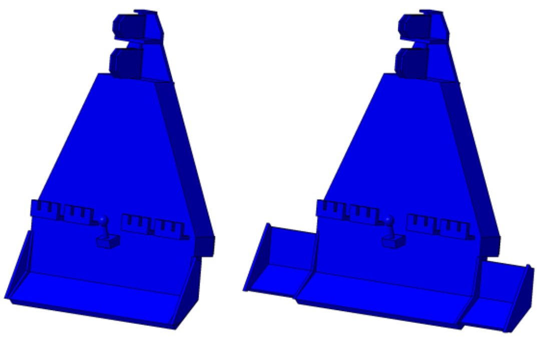

Figure 35. Extractable extensions (concept 3)

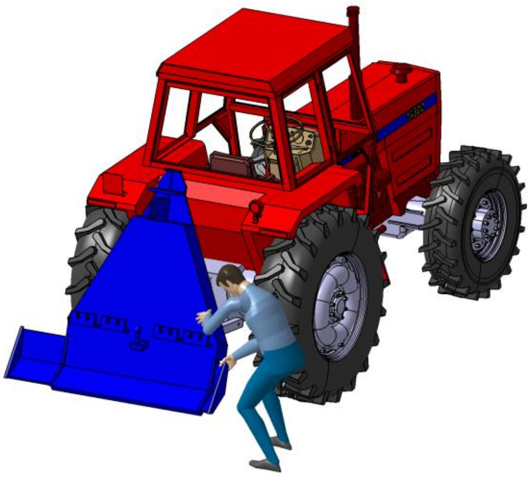

Figure 36. Posture analysis for concept 3

ule, a virtual manikin was placed in the position of maximum stress that the user could assume during the operation of the equipment. Once the digital humans were positioned, we switched to the Human Posture Analysis module in order to perform ergonomics analyses on the manikin. Two instruments were chosen for this phase: RULA Analysis and Biomechanics Single Action Analysis.

For concept 1 we simulated two postures:

- Posture 1: the posture kept by the operator to take the additional parts of the blade from the supports positioned in the upper part of the main frame;
- Posture 2: the posture maintained to put the blades to the supports at the bottom.

For concept 2 we simulated the posture kept by the operator to grab the blade on the back of the skidding winch and then rotate it.

For concept 3 we simulated the posture kept by the operator to pull the additional blade from the sub frame (Figure 36).

The workers postures were evaluated using the PEI, developed and illustrated by

Table 22. Statistical distributions related to pulling operations

Operation	Units	Distribution	Expression	Test	P-Value
Preparation	s	Weibull	6 + WEIB(56.2, 1.15)	K-S	> 0.15
Felling	s	Erlang	37 + ERLA(61.6, 1)	K-S	> 0.15
Cross-cutting	s	Beta	29 + 921 * BETA(1.17, 2.83)	K-S	> 0.15
Delay	s	Weibull	2 + WEIB(48.4, 0.598)	K-S	> 0.15
Pulling	s	Beta	4 + 313 * BETA(1.26, 2.07)	K-S	> 0.15
Travel empty	m/s	Lognormal	EMPIRICAL	K-S	< 0.01
Travel load	m/s	Lognormal	LOGN(1.09, 1.28)	K-S	> 0.15

Table 23. Statistical distributions related to forwarding operation

Operation	Units	Distribution	Input Analyzer Expression	TestP-Value
Travel empty	m/s	Beta	1.2+1.8*BETA(1.97, 1.43)	K-S > 0.15
Maneuver	s	Beta	12+473*BETA(1.47, 2.67)	K-S > 0.15
Load	s	Triangular	TRIA(588,1.06e+003,2.8e+003)	K-S > 0.15
Travel load	m/s	Triangular	TRIA(1.11,2.15,2.59)	K-S 0.086
Discrete events	s	Exponential	18+EXPO(220)	K-S > 0.15
Delays	s	Exponential	62+EXPO(385)	K-S > 0.15
Unload	s	Beta	285+1.18e+003*BETA(0.828, 1.4)	K-S > 0.15

Di Gironimo et al. (2004).

Results

According to Akay et al. (2004), the harvesting system has to be chosen balancing it for the forest's characteristics, depending from machine types and intensity of the harvest operation to reflect variable factors that affect the productivity of the equipment.

We chose the DES approach to analyse the real case and study the impact in productivity adopting an alternative process. For this step of the study, we followed the same methodological approach proposed by Hogg, Pulkki, and Ackerman (2010).

In particular, thanks to the simulation phase, we proved how much the process of timber harvesting benefits from a different extraction technique using a tractor-trailer combination, combining a skidding system with a forwarding system. Removal of logs it's done with minimal damage to the residual stand, using a small manoeuvrable skidding machine. In fact, a trailer is less likely to be able to get to the log because of its size and handling features, like ability to turn in the woods. On the other side, during the forwarding step the vehicle stays on well-marked trails, as recommended by Masson and Greek (2006).

With reference to the real process, the data coming from the time study, and processed for the implementation inside the DES software, generated 7 distributions. Only one of these distributions was statistically rejected (Table 22). The rejected distribution returned a P-Value of less than 0.01 performing the Kolmogorov-Smirnov test; an empirical distribution was therefore required to describe that data

Table 24. Results of the DES simulation in terms of productivity

Distance [m]	Skidding Productivity [kg/h]	Forwarding Productivity [kg/h]
50	3210	7275
100	3200	7175
150	3177	7025
200	3113	6975
250	2930	6825

Table 25. Results of the ergonomic analysis

Concept	Posture	LBA	OWAS	RULA	PEI
1	1	900	1	3	1.20
	2	3435	3	6	3.21
2		3503	3	7	3.43
3		2963	2	3	2.14

set inside the DES software. For the alternative process, the data proved to be enough robust to fit all the statistical distributions evaluated in the Input Analyzer software (Table 23). The results of the simulation showed that with the combined pulling-forwarding process is possible to achieve a substantial increase in productivity (Table 24). Forwarding, in comparison with skidding, guarantees a productivity growth from 121% to 133%.

The results of the survey administered to experts are reported in Table 26. All statements of the set of 10 possible customer needs, achieved an average score of at least 4. We used QFD capabilities to identify relationships between user requirements and the derived design parameters; the same approach is carried out in a study by Sørensen et al. (2010). In the CAD design phase, we adopted the same approach of Di Gironimo, Lanzotti, et al. (2012). Table 25 summarizes the results of ergonomics analysis. The best value of PEI is related to the concept 3, which uses extractable extensions. Figure 37 shows the final concept.

Future studies could cover the evaluation of costs in terms of fuel consumption, manpower and equipment, in order to see how the increase in productivity given by the adoption of the tractor-trailer system affects the capital expenditure and operating expenses.

Table 26. Results of the survey

Mean score	Customer need
5.00	High productivity
4.90	Back rollover prevention
4.90	Lateral rollover prevention
4.90	Prevent cable break
4.90	Damage to remaining stand trees and plants must be prevented
4.30	Ease of loading operation
4.20	Back tires protection
4.00	Soil damage must be prevented
4.00	Capability to pull in high density stand
4.00	Capability to pull in high slope conditions

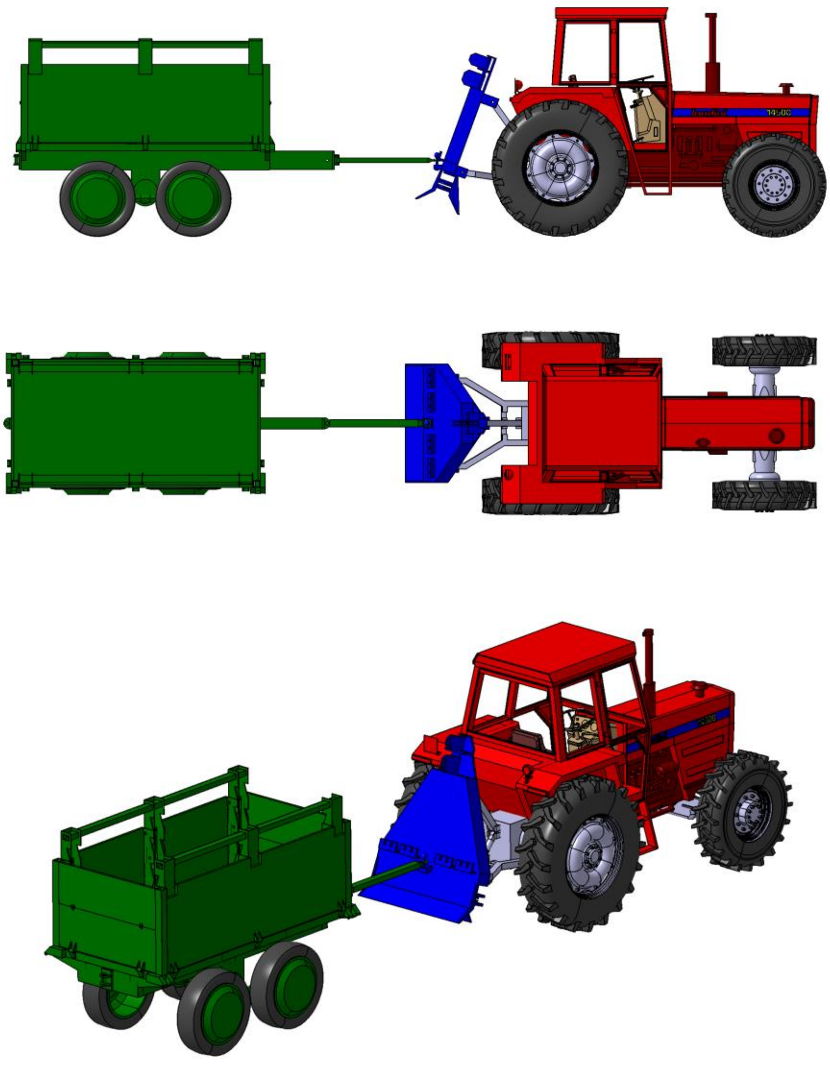

Figure 37. Final concept of skidder and trailer

4 Conclusions

In an initial concept design stage, due to the early nature of design activities, product knowledge is still incomplete. Above all, requirements are uncertain and sometimes conflicting. Thus, design solutions are supposed to be drafted in an incomplete requirements environment. The methods illustrated above were integrated to deal with such this situation. We proposed integrated techniques to achieve solutions limiting the risks arising from the lack of product knowledge. In complex situations, this approach provides the opportunity of proceeding iteratively, refining and completing the requirements, without the need of leaving the conceptual design. In particular, the results coming from the case studies showed the following outcomes.

We used QFD to identify relationships between user requirements and the derived design parameters. This approach provided an efficient way to collect and prioritize demanded quality elements. Technical conflicts were managed with the contribution of the TRIZ toolbox. This method allowed the generation of several innovative solutions that are compliant with the product's requirements; moreover, the concept solutions do not need to be the result of compromise between technical features in conflict, in opposition to the established approach, particularly evident in the traditional usage of the House of Quality. For systems in which reliability and safety are vital, such as for a nuclear fusion reactor, the application of FMECA to a conceptual stage gave the opportunity to highlight critical product functions of the design concept. Therefore, this approach give the designer the opportunity to focus his efforts on the aspects that could lead to the reduction of system failures' criticality. In situations in which process aspects are involved and are of paramount importance, such as in forest harvesting, we chose to adopt DES to study the impacts of implementing alternative processes. One of the main key benefits of this approach is that DES gives the opportunity to create stochastic models that represents uncertainty much better than any deterministic model. Knowing the field of variation of the objective function (such as productivity or projected costs), designers and entrepreneurs will be best equipped to make their decisions. The concept review phase was managed adopting an immersive virtual reality environment to compare simultaneously product alternatives. A valuable contribution in this phase came from the adoption of kinematic simulations for complex mechanical systems and ergonomic assessments in VR for products that require man-machine interaction. The review process was speeded up conducting the evaluation of concepts with AHP, which allowed the prioritization of the solutions based on both qualitative and quantitative criteria selected for their importance in the choice, allowing the selection of an optimal solution.

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