About the Introduction of a Dialogue-Based Interaction within CAD Systems

Niccolò Becattini[1], Yuri Borgianni[2], Gaetano Cascini[3] and Federico Rotini[4]

[1]Politecnico di Milano (Italy), niccolo.becattini@kaemart.it
[2]Università di Firenze (Italy), yuri.borgianni@unifi.it
[3]Politecnico di Milano (Italy), gaetano.cascini@polimi.it
[4]Università di Firenze (Italy), federico.rotini@unifi.it

ABSTRACT

CAD systems are nowadays extending their domain of application towards the preliminary phases of the design process, with the emergence of Computer-Aided Innovation ð CAI. However, the first generation of CAI commercial software is far from achieving the intended objectives; among them, the diffused TRIZ-based systems made no exception. Particular limitations are highlighted within the embodiment design stage with reference to the support provided by CAx tools in fulfilling product specifications, whenever the generated solutions do not satisfy system requirements.
The authors propose to overcome the current limitations by implementing a dialogue-based system into the framework of existing CAD applications, to support the designer in overcoming problems emerged during the initial design stages. The manuscript illustrates a refined set of requirements for a Dialogue-Based CAD system according to the outcomes of a testing campaign carried out with a preliminary version of a question-answer framework. The proposed instrument is capable to measure the achievement of all the major characteristics highlighted by the survey of established models for carrying out embodiment design.

Keywords: dialogue-based interaction, innovation, embodiment design.
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1 INTRODUCTION

The growth of computational capabilities and the demand of consistently reducing lead-time guided the evolution of Computer-Aided tools during the last decades. Software evolved from single-purpose geometrical modelers towards more comprehensive and diversified systems that support several stages of the product development cycle, with a major reference to the finalization of the design and the use of the developed virtual models for manufacturing purposes.

Despite the massive diffusion of machines with computational resources much higher than any human brain, still no artificial system is capable to manage the complexity of the whole design task, which, rather than a fully integrated process, can still be seen as a sequence of three distinct stages: conceptual design, embodiment design, and detailed design [1].

Conceptual design, defined in [1] as ôôa search across an ill-defined space of possible solutions, using fuzzy objective functions and vague concepts of the structure of the final solutionôô, is acknowledged to be the most influential design stage in determining the characteristic product features. The interest towards the support of the conceptual design stage through computer applications has been emphasized by circumstances pertaining to the evolution of industry and market.

Indeed, the opening of a new industrial era whereas competition is strongly based, beyond productivity and quality issues, on the firmsô capabilities to innovate [2], has affected also the evolution of Computer-Aided applications. Their focus has been switched to the initial engineering design tasks, which dramatically impact the final characteristics of the product and thus its degree of innovativeness, constituting in turn a key feature for the success in the global marketplace. As they are extending their domain of application upwards the preliminary phases of design and by attempting to manage more abstract representations of the product, CAD systems are still far from systematizing the conceptual design phase and markedly those activities requiring to leverage inventive skills. Moreover, a great concern is constituted by the missing link, in the computer environment, between the development of a conceptual solution and the subsequent definition of the product layout and geometry. In this sense, a major limitation can be identified in the common structures and interfaces of CAD/CAE systems, which are not conceived to allow fast input and representation of concept models. Consequently, they erect psychological barriers in experimenting new types of solution ideas and do not provide any support to designers in developing and expressing their creativity [3, 4].

Recently, Computer-Aided Innovation (CAI) systems have started addressing these lacks [5], attempting to exploit, in most cases, the potential of TRIZ [6], i.e. the Russian acronym for Theory of Inventive Problem Solving. This branch of Computer-Aided tools aims at supporting innovation and fostering individual creativity, either in case it is required to design a new product from scratch, or to cope with a non-routine design problem emerged during design development. Most of them support the representation of abstract information, e.g. the functional description of a technical system and/or the causal relationships between design choices and system performances; some others introduce stimuli for widening the range of alternatives, e.g. by the suggestion of physical/chemical principles or by reusing already existing solutions available in databases.

It is worth to highlight that a few preliminary experiments to embed the principles of TRIZ within CAD systems have been experienced, giving rise, as reported by [7-9], to promising, but still not satisfactory, results. The major problem seems to consist in a marginal support to users with limited design experience and poor background in TRIZ. Besides, the domain borders of this emerging technology are still fuzzy and, in any case, CAI systems suffer of limited interoperability with downstream CAx tools [10], starting from the applications that support embodiment design.

It is assessed that the innovation process is considerably influenced also by the adoption of suitable methods and tools in the embodiment design stage, whose related decisions involve a not negligible amount of risk [11]. Still according to [1], embodiment design works on an initial design configuration (selected during the conceptual design stage) and aims at further specifying the general layout of the whole system. Very often the corrections to be made require radical modifications to the initial layout, resulting in iterations from embodiment to conceptual design and vice versa [12]. Such iterative behavior is widely motivated by the different nature of the objectives characterizing conceptual and embodiment design.

More specifically, during the conceptual phase, designers have the need to explore novel working principles for the implementation of the primary function of the system. Original and innovative solutions can be developed only if such a task is accomplished without focusing on conventional ideas. To this end, Pahl and Beitz [1] suggest an abstraction path aimed at identifying a generalized form of the problem to be addressed, starting from a careful analysis of the design requirements. The recalled process compels to concentrate the design efforts mainly on the functional requirements, omitting those that have little bearing on the main technical function. On the other hand, during the embodiment phase the designer should develop the conceptual solution up to the point that subsequent detail design leads to the production stage. Therefore, the embodiment phase requires to design specific features of the solution taking into account the whole collection of requirements. Hence, during this stage, the product model evolves by considering technical and economic constraints or even aesthetical properties [13]. The requirements to be consequently fulfilled can give rise to conflicts among design features not compatible within the developed layout, motivating thus the iterative process between embodiment and conceptual stages.

Since such iterations negatively impact the efficiency of the design process, a new method should be focused at avoiding, at the maximum extent, corrective steps during the initial design phases.

According to [11, 14], Computer-Aided optimization systems applied during the whole design cycle are candidate means to improve design efficiency. Nevertheless, the optimization logic approaches the problem of conflicting requirements by individuating the best compromise. It is worth noticing that trade-off solutions are typically less competitive and have a shorter perspective since, according to TRIZ, technical systems evolve by overcoming, and not compromising, contradictions [6]. Besides, optimization strategies enhance the efficiency of the product development process, but can lead, on the other hand, to shortcomings in terms of effectiveness of the design task, due to poor potential of compromise solutions.

In this perspective, the definition and fine-tuning of Computer-Aided systems capable to support the development of design embodiments beyond the adoption of trivial trade-offs can represent a desirable trajectory within the evolution of CAI systems. The paper investigates the field of support systems aimed at enhancing the outcomes of embodiment design and, on the basis of conducted experiments, proposes a set of requirements for a new Computer-Aided Innovation tool.

With such objective, Section 2 analyzes current strengths and weaknesses of established cognitive and systematic methods, which are considered relevant for CAD system during embodiment design. On these bases, it further illustrates the potential benefits arising by the implementation of a dialogue-based system. Section 3 is dedicated to describe the setting of an experiment regarding the interactions between designers and a question-answer framework, capable to provide valuable cues for the development of CAI systems for embodiment design. The results of such experiment are reported in Section 4 and further discussed in Section 5, which includes the conclusions and the planned future activities within the present research.

2 ABOUT THE REQUIREMENTS OF A CAD SYSTEM SUPPORTING CREATIVITY DURING THE EMBODIMENT DESIGN STAGE

The success and the efficiency of the whole product development process dramatically depends on the designers’ ability of producing a few, but promising, solution concepts. In order to achieve this goal, it is also necessary to produce a preliminary layout of the solution capable to satisfy the requirements without negatively interacting with other systems or with the environment as well. In other words, the capability to easily tackle non-routine design problems occurring during the development of technical systems represents the key for obtaining valuable solutions [15].

In the following, a brief review of some cognitive and some systematic problem solving methods is presented with a double goal. First, to show the advantages and drawbacks of their implementation within a computerized system. Second, with a wider angle, to determine the qualitative characteristics of an enhanced Computer-Aided system for supporting the embodiment design phase. The characteristics used for comparison purposes are further detailed in section 2.5. They are related to the flexibility of the approach with respect to the different contexts/requirements a designer might encounter, to the capability to stimulate creative thinking and a holistic vision, to the potential effectiveness and efficiency of the process.

2.1 TRIZ and the Algorithm of Inventive Problem Solving (ARIZ)

TRIZ body of knowledge is composed by different models and tools for describing systems and solutions at different levels of abstraction. All those elements are integrated in a step-by-step algorithm (ARIZ) that supports the cognitive processes of the designer through the whole problem solving process. From the identification of a contradiction (namely, two conflicting requirements determining a problem), a designer is guided towards the analysis of the physical interactions between system elements, in order to describe the problem as two opposing value assignments for the same design parameter. In other words, within an embodiment design stage, the algorithm allows the designer to efficiently reflect just on the part of system geometry causing the problem, focusing on its working principles and operating conditions. Afterwards, further conceptual steps are in charge of undertaking the above problem model for synthesizing the solution with dedicated cognitive instruments supporting this process. For example, during the stage 5 of the ARIZ algorithm, the designer can apply criteria for identifying potential modifications in system geometry and dynamics (or both of them) in order to redesign the embodied system. Rather than simply choosing the best compromise for a given design parameter, those criteria stimulate the reflections on strategies capable to fully satisfy both the conflicting requirements. In this regard, the role of the designer is crucial: the well-structured sequence of logic steps aimed at stimulating the thinking process, such as the designer’s creativity and his/her tacit knowledge is essential to generate a suitable solution. On the other hand, explicit knowledge also plays a role in widening the problem space; the search within databases collecting already discovered physical, chemical or geometrical principles, as well as patent corpora, supports the identification of alternative solutions, by using different behaviors to perform the desired functions.

ARIZ is characterized by an intrinsically effective approach for the determination of a solution. Indeed, the re-embodiment process must be carried out by taking into consideration the requirements to be satisfied just in the physical zone and under the conditions in which the problem appears. Moreover, the designer is forced to solve the problem using at the maximum extent the already available resources, changing the system as little as possible. However, the overall efficiency of the whole process is affected by the considerable amount of time required to master this kind of algorithm in order to proficiently use it.

2.2 Case-Based Reasoning (CBR)

Case-Based Reasoning [16], through its structured sequence of steps, represents one of the most powerful cognitive methods currently available for problem solving, among those implementable through Artificial Intelligence (AI) algorithms. In details this method is composed by 4 different phases presented by some authors as the ò4 Ró: òRetrieve, Reuse, Refine and Retainó. Once a problem has been structured according to a specific framework, a computerized system carries out the first step (Retrieve) by recognizing its main features and requirements in an indexed database of already solved problems, with the purpose of reusing an analogous stored solution. Once the computer extracts a potential suitable solution (Reuse) from the database, the designer is just in charge of adapting it to the specific case under investigation by fine-tuning (Refine) the values of design variables. As a non-computerized cognitive approach, the knowledge acquisition process ends with the storage (Retain) of the new case, e.g. the couple problem-solution, in the database.

The integration of such a method within the broadly diffused product development techniques supported by data management systems [17] allows to improve the efficiency of the problem solving process by using the internal resources of a company at the maximum extent: already adopted solutions can be easily applied with a modular approach to products under development, with the multiple goal of simplifying the design process, preserving the main structure of the manufacturing processes and of the assembly procedures. On the other hand, the potential of searches among sets of similar or analogous solutions is limited by previous experiences and by the size of the database of successful cases. The search for a suitable solution requires a reasonable amount of time, but this activity may also result in a common trade-off or, worse, in a vain attempt. In this regard, the method demonstrates a good flexibility of use when applied in the scope of a specific industrial field, but it suffers poor repeatability when applied to a wider range of technical contexts, as usually happens with current complex systems. Tacit knowledge and creativity take part in the problem solving process just when the designer has to carry out the refinement phase, but no particular support is provided for such purpose, limiting the opportunities of identifying radically innovative embodiments capable to generate a considerable competitive advantage.

2.3 Constraint Satisfaction Problems (CSPs)

Constraints Satisfaction methods [18] allow to tackle CSPs, a highly formalized class of problems whose objective, in design, is to find a set of values, within a definite range of variability, to be attributed to system parameters in order to fulfill all the requirements at a time. With reference to the embodiment design phase, such an approach allows to describe the solution space with a greater number of constraints, including, according to [19], performance specifications, design variables and their mutual relationships. A dedicated computer algorithm searches for suitable solutions by simulating different system configurations and architectures. However, this DoE-like approach underlies an optimization-oriented solving procedure that shows its main limitations whenever an over-constrained situation appears. In such cases there is no combination of values for system parameters capable to satisfy conflicting requirements. Despite several CSP methods for facing over-constrained problem exist, they just provide solutions of incremental nature. Indeed, all of them are based on trade-off logic: the designer, on the one hand, can just set priorities among requirements to be satisfied or, on the other hand, can just widen the range of acceptable values for system variables. Therefore, there is not any specific means capable to support the designers in leveraging their tacit knowledge. Each extension of the design space, e.g. through the introduction of a new system variable, or by changing the boundaries of an existing one, is completely due to personal experience and individual skills. Conversely, explicit knowledge is crucial since the relationships between design variables and system requirements drive the simulations aimed at defining a suitable system configuration. In terms of efficiency, this process may lead to radically different results: in absence of conflicting requirements, the computational time for obtaining a suitable solution just depends on the number of design variables involved within the project. On the contrary, when conflicting requirements do not allow to simply optimize system parameters, it is not sufficient to carry out iterations within the algorithm until convergence, since just a compromise solution would be achieved with consequent poor design innovativeness.

2.4 Brainstorming

Brainstorming [1] probably represents the most famed problem solving method, usually seen as the main reference approach for tackling problems requiring creativity and inventiveness. This unstructured process does not proceed with a systematic approach; new ideas are generated by leaving full thinking freedom to designers and avoiding their criticism. The flow of solution concepts, within the group of open-minded people taking part to the session, is due to both the individual capabilities of reasoning by analogy and the stimulation of other participantsʼ ideas.

By its collaborative and free nature, it constitutes a good chance for supporting the engineering multidisciplinary nature of the design process, although the abstract level of representation of solution concepts can hardly take into account geometry related requirements as they emerge during the embodiment stage. Even if it leverages tacit knowledge at a maximum extent, the whole process efficiency is its most relevant shortcoming. Indeed, without any form of dialectic reflections, it can lead to a lot of bizarre trials, rather than a few technically and economically feasible solutions. In opposition to TRIZ, the search for solutions is not focused on the zone where the conflict appears; the contradictory requirements to be satisfied can be vaguely defined, resulting however in a casual search through an unlimited problem space without relying on any element of explicit knowledge.

At last, from the perspective of computer implementation, the absence of a structured form that systematizes reflections constitutes an additional, besides considerable, limitation.

2.5 Profile of a Computer-Aided System for Supporting the Embodiment Design Stage

All the above-mentioned considerations demonstrate the importance of guiding individuals along the two main steps of the early design stages, i.e. conceptual and embodiment design. From a certain perspective, the efficiency of the whole design process relies on the capability of carrying out both problem analysis and solution synthesis according to a systematic path addressed at the achievement of clearly stated objectives, thus avoiding trials and errors. Conversely, it is also necessary to leverage individualsʼ experience. Recognizing similar patterns between problems is of paramount importance: the purpose is to beneficially apply established solving strategies for overcoming the faced design limitations. Thus, abstraction and reasoning-by-analogy are the key for bridging fields of technique apparently far from each other and subsequently synthesizing innovative and valuable solutions.

Further dichotomies emerge by the analysis of the problem solving methods presented in the previous paragraphs. The solving procedures, on the one hand, should be general to be easily applied to problems appearing within different technological contexts; on the other hand, they should also be as focused as possible on the nature of the problem itself (being it related to the improvement of functionality as well as the removal of drawbacks) in order to reduce the space for searching solutions. The achievement of such requirement constitutes a viable condition for carrying out the design steps with the maximum efficiency, while focusing on the system layout and the physical zone where the problem appears. Table 1 summarizes how the examined problem solving approaches actually fulfill the demands of a new computerized system supporting the early phases of the design process.

Problem Solving method	*Flexibility according to the problem*	*Applicability in different contexts*	*Stimulation of designers' creativity*	*Efficiency of the process*	*Satisfaction of conflicting requirements*	*Focus on System Layout*
TRIZ/ARIZ	Good	Quite Good	Good	Poor before mastering the method	Good	Good
CBR	With designersô adaptation	Very poor	Absent	Depending on the size of solutions database	Depending on previous solutions	Depending on problem nature
CSP	Good	Good	Absent	Excellent for optimization problems	Absent	Good
BRAINSTORMING	Good	Good	Good	Very poor	Not supported	Very Poor

Tab. 1: Level of achievement of common characteristics among the presented problem solving methods.

Among the examined problem solving methods, TRIZ and its main instrument ARIZ represent, according to the authorsô vision, the most promising approach for satisfying all the discussed requirements. Nevertheless, the preliminary attempts of their implementation in Computer-Aided Innovation tools resulted in a mere collection of elements from the TRIZ body of knowledge with a very poor usability for non-experts. Moreover, all those applications have no factual links with any other Computer-Aided tool supporting design activities. In this regard, the introduction, within a computerized framework, of a structured method supporting the early stages of the design process still represents an open issue.

In order to overcome the existing limitations of current Computer-Aided Innovation systems, the authors suggest embedding a TRIZ-like problem solving process in a software application through a dialogue-based questionnaire. Dialogue-based software tools are already widely used in different design contexts, from the elicitation of product requirements to their verification after the completion of the detailed design phase. The adoption of natural language rather than technical jargon improves the usability of a candidate dialogue-based system, also due to the relevance, within design practices, of human face-to-face interactions, despite the spread of ICT [20]. Besides, structuring the dialogue through a questionnaire allows coping with the problem according to a procedural sequence, dedicating more attention to facets that result the most critical.

Generally speaking, each conversation among humans affects cognitive processes of involved subjects. From the viewpoint of computer implementation, this means that a dialogue-based interaction may give rise to substantial reflections of the designer along the problem solving process, helping to change the problem perspective and to consider design alternatives. Moreover, designers experienced in detailed design phases often suffer of poor exposition to methods and techniques for supporting the first design steps of the product development process.

The construction of a software prototype according to the above-mentioned profile would require a huge amount of time for both its development and the verification of conversational sequences. On the other hand, the analysis of the dialogue-based interactions between individuals is a well-developed practice within the whole branch of design protocol analysis. In this regard, the following section describes an experiment, showing how a simple questioning procedure may affect the analysis of a problem, with the short-term purpose of sharing a common framework for analyzing designersô behavior and aptitude towards embodiment design tasks. The authors assume that the results of such examination should provide directions for enriching and refining the set of requirements to be fulfilled by a Computer-Aided tool for embodiment design. According to the authorsʼ vision, such a module should be embedded in the next generation of CAD systems, so as to efficiently enlarge their applicability since the earliest design stages.

3 PROTOCOL ANALYSIS OF DESIGN REASONING SUPPORTED BY A PROBLEM SOLVING QUESTIONNAIRE

With the aim of presenting the potential support of a computer implemented dialogue system, the paper presents an investigation about a dialogue-based interaction between a designer and a computer within an embodiment design task. According to this objective, the authors have formulated a set of typical questions to investigate the core of a design problem arising during the embodiment stage. The aspects raised by these questions commonly play a relevant role when a design concept has been developed, but some requirements are not fulfilled. The content of the answers should be employed to evaluate which reasoning capabilities are mostly stimulated during a design discourse supported by a dialogue tool. Thus, the answers have to be recorded or collected in order to subsequently perform a protocol analysis task.

As previously recalled, the construction of a computer-based tool to evaluate strengths and weaknesses of a dialogue-based system, assisting embodiment design, would require a long development time. Besides, the fashion through which questionnaires are administrated just slightly influences the outputs of any dialogue, as assessed in [21]. Therefore, in order to shorten the set-up time for performing any test, a paper-based version of the questionnaire has been preliminarily produced. Such form of administering the questions easily allows the maximum flexibility for the designers to answer the complete sample of queries, by assigning no established sequence of the questions.

3.1 A sample of Questions to Investigate Problems Emerging within Embodiment Design

The set of questions is hereby presented in the order the authors would follow to elucidate the main issues of the problem and individuating the conflicting requirements to be overcome for obtaining a valuable solution. However numerous sequences, also according to designersʼ interpretation, can result as logical patterns for problem setting and solving. Their formulation contains just general terms to cover the widest set of technical and industrial problems, as illustrated in the followings:

- A. Briefly describe the core problem of the technical system under investigation (maximum 30 words).
- B. What technical function should be carried out in order to satisfy the needs of the end users employing the device under study?
- C. Remark who or what undergoes the modifications carried out by the technical system that is described.
- D. Describe the most impacting undesired/harmful effect/condition (including underperformances and further missing functions) that emerges in the described situation.
- E. With reference to the undesired phenomenon or unsatisfactory aspect of the case study, clarify who or what mostly perceives the bad consequences that arise.
- F. Which element(s) cause(s) the problem described in the case study? Clarify if such component performs any positive function.

In the authorsʼ intentions, the first question is aimed at focusing on the context of the problem, identifying the primary source of the occurring conflicts. The subsequent dialogue-based interactions provide additional elements for reasoning about the functions that are satisfactorily achieved (B, C) and the current inconveniences of the designed layout (D, E, F).

3.2 Protocol Analysis of the Design Discourse

The text reported by a designer can be subjected to protocol analysis, identifying the most relevant features of the performed discourse, that allow to deduct the potential impact of a small-scale dialogue system. The authors have individuated a minimal set of parameters concerning the reasoning followed by the designer, with the purpose of providing indications about the level at which all the requirements of problem solving methodologies (summarized in Table 1) might be fulfilled through a dialogue interface. The part that follows motivates the links between the features characterizing a design procedure and the design reasoning, whereas the latter is highlighted in italics.

The flexibility of the system according to the treated case study, as well as the applicability of the tool in differentiated contexts, can be achieved when the supported design task resorts to an abstraction process of the problem, stimulating a reasoning based on analogies [22, 23]. The *Generalization* characterizing the answers provided during the dialogue can be thus considered a symptom for the versatility of the implemented system to serve diverse technical fields.

The designer's creativity is stimulated whenever he/she is capable to outline or sketch a new model of the system, thus an improved architecture or layout. According to the design categories widely used to perform protocol analysis and introduced by Gero and McNeill [24], i.e. Function Behaviour Structure (FBS), such circumstance is met when an individual makes reference to the structural level of the problem, after reflecting upon issues related to functional requirements and aspects dealing with the behavior of the system. The frequency of the redefinitions of the design structure or layout (*S-redefinition cycles*) is thus hereby considered as a manifestation of a creative generation mechanism.

With regards to the efficiency of the design problem, the Introduction of the paper has already pointed out how a long series of iterations between the embodiment and the conceptual level of the design process negatively affects the time required to complete the task. In this sense, a clear view of the present conflicts between not reconcilable demands, at least within the chosen design layout, helps in avoiding unnecessary additional iterations. Thus, whereas a computerized support system can help the user to concentrate on the current situation, depicted through the occurring contradictions, the design process will benefit in terms of efficiency. As a consequence, considerable advantages would arise if the employed dialogue-based system owns the capability to suggest the designer a problem representation swiveled on the description of the conflicting requirements and focused on the design variables that give rise to them (*Contradiction formalization*).

The capability of the tool to support the problem solving process, and thus the overcoming of the identified conflicts, strongly depends on the global representation of the design situation arisen through the questionnaire. In essence, the coherence and the carefulness of the originated design discourse (*Correctness*) represent a major factor influencing the subsequent identification of a valuable solution, making use at a large extent of the individual tacit knowledge.

Eventually, in order to avoid the emergence of odd solutions, characterized by poor feasibility, the design process should be maximally focused on the structural level of the encountered problem. Thus, at the embodiment stage, the design reasoning can result beneficial if the speculation about functions, goals and system behaviors is substantially finalized to translate new ideas into effective modifications of the starting layout. As a consequence, the protocol analysis highlighting the iterations between FBS categories should advantageously reflect a considerable number of design reflections at the hierarchy pertaining the structural level (S-diffusion rate).

On the basis of the above provided evidences, the next step consists in proposing metrics to evaluate the parameters characterizing the design reasoning, summarized in the first column of Table 2, which recalls their link with the desired properties of a computer-aided tool for embodiment design.

3.2.1 A proposal to measure the parameters characterizing the design reasoning

The protocol analysis, conducted through the FBS criteria, primarily reveals the flow of the design discourse, focusing to the sequence of different hierarchical aspects of the system that are considered. A FBS graph, highlighting such process is reported in Fig. 1, as an exemplary case extracted from the analysis of a design reasoning performed throughout the proposed dialogue-based system. The diagram remarks the hierarchies of the problem treated by the designer with reference to each answer provided during the questionnaire, according to the chosen sequence.

Parameter concerning the design discourse	*Flexibility according to the problem*	*Applicability in different contexts*	*Stimulation of designers' creativity*	*Efficiency of the process*	*Satisfaction of conflicting requirements*	*Focus on System Layout*
Generalization	ŏ	ŏ				
S-redefinition cycles			ŏ			
Contradiction formalization				ŏ		
Correctness					ŏ	
S-diffusion rate						ŏ

Tab. 2: Aspects of the design discourse, evaluable through protocol analysis, which represent clues about the fulfillment of matched desirable properties of CAD systems (as remarked by the dots).

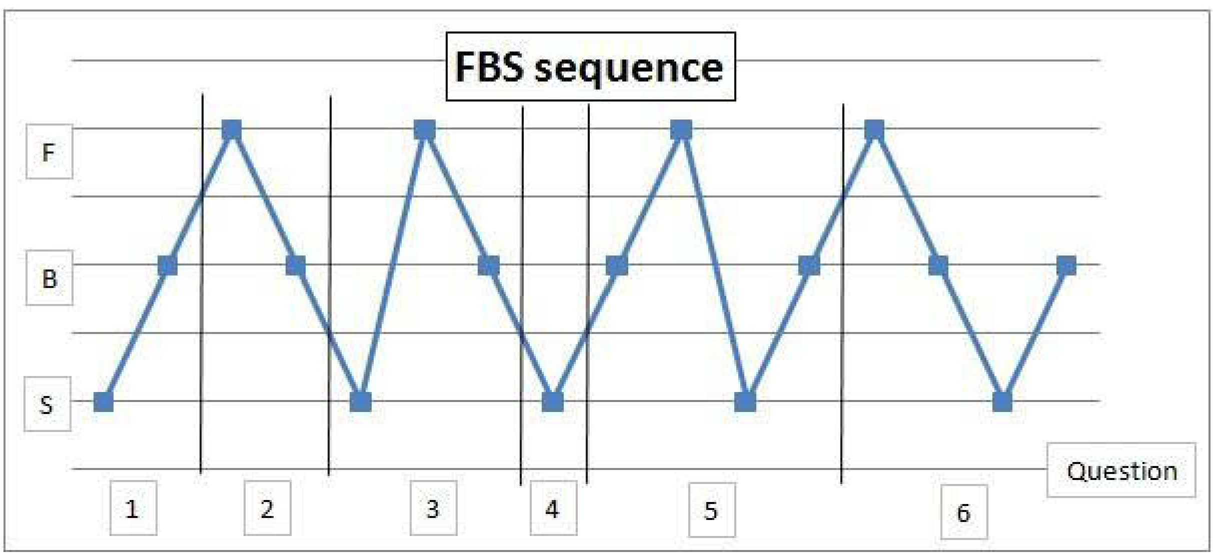

Fig. 1: Exemplary protocol analysis of a design process in terms of the features pertaining the FBS levels.

The *S-redefinition cycles* and *S-diffusion rate* parameters can descend from such kind of protocol analysis. The former is defined as the number of times the designer returns to analyze the structural level of the problem, hence the amount of òhillsó depicted in the FBS graphs (thus 4 for the example of Fig. 1). The latter is determined as the relative frequency of steps dealing with the system architecture with respect to their whole number (thus including the reflections upon functions and behaviors); hence, the parameter assumes the value 5/16å0,31 for the illustrated case.

The *Generalization* of the provided description is evaluated by surveying the contents of each answer with respect to an assigned text, describing the problem. As an evidence, this measure can be attained for testing purposes, but it is not consistent with the actual work through CAD systems during embodiment design. Each answer has the highest generalization score if the tester describes the problem employing terms depicting the relevant system features without mentioning the system itself. Such a description conducted by attributes with minimal references to specific system elements would result in the capability of the design support tool (and of the designer) to illustrate situations referable to different contexts and industrial domains. An intermediate score is assigned whether the designer introduces more general terms than those introduced in the provided text, e.g. through the employment of hypernyms (such as metal instead of iron, animal instead of dog, etc.). The lowest score is attributed if the provided answer includes just words introduced along the text or their closer synonyms.

The rate expressing *Contradiction formalization* is evaluated with reference to the basic overview of the problem that should be provided through the answer to the question A. The highest score is attributed if two conflicting requirements and a key design variable responsible of the contradiction are delineated. An intermediate score is assigned to those answers capable to focus on at least two of the aforementioned items (typically two conflicting engineering characteristics, or in the form of positive consequence on a certain requirement by introducing a certain modification in a design variable but without mentioning the negative consequence on another system feature). In the other cases the lowest score is supplied.

Eventually, the *Correctness* of the analysis is estimated by considering how well the designer has reported, across the answers to the questionnaire, the information that is crucial to problem solving, through which to form the primary problem representation [25]. The evaluations provide a high, intermediate and low score.

4 EXPERIMENTAL ACTIVITY AND OBTAINED RESULTS

4.1 Organization of the Experiment

The test of the proposed dialogue-based system has been performed by a sample of convenience constituted by 33 MS students in Mechanical Engineering, which can be thus considered freshman designers. The participants have been invited to carry out a design reasoning through the use of the presented six questions, after being exposed to a design solution through a CAD model (Fig. 2) and a brief textual explanation of the encountered problem. The experimenters were asked to elaborate a logical design discourse by joining the answers to the queries in the sequence they judged the most appropriate.

The treated case study, concerning a real industrial problem about the design of a circular saw, can be seen as a typical product development task faced during the embodiment design, since additional requirements have to be discussed after the kinematics of the system has been defined and a physical layout has been consequently built. Whereas a topical detail of the modeled system is presented in Fig.2, the explaining text is reported in the followings:

"Circular saws are commonly constituted by a housing, that hosts the engine coupled with the circular blade, and a base mounted on the housing itself to support the saw on the piece to be cut. The base is mounted on the housing in such a way to allow the turning movement around a horizontal axis, so to adjust the inclination of the blade with respect to the base, according to the desired cutting angle. The range of the adjustment angle is commonly 45°; as a consequence the relative angle between the blade and the base can vary between 90° and 45°. However it is often necessary to perform different cuts, that require inclinations until 38,5° and thus needing an adjustment range of 51,5°. The adjustment mechanism includes the base with a reference hinge (around which to allow the turning movement of the housing and the rest of the saw), a connection beam with an eyelet for the adjustment, a blocking nut. The ends of the eyelet act as a stop for the adjustment. The most common cutting angles (90° and 45°) have to be easily and accurately adjusted. However eyelets with a range greater than 45° (like those of the saws allowing the cuts until 38,5°), don't allow to position the blade at 45° with respect to the piece in a quick and accurate way".

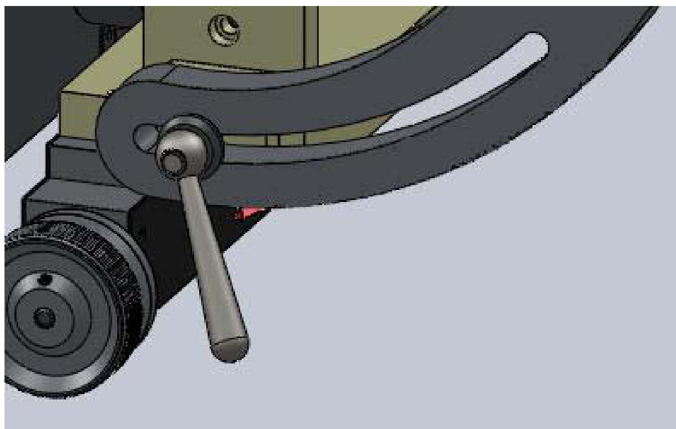

Fig. 2: CAD representation of an eyelet to adjust the inclination of a circular saw.

4.2 Examination of the Written Dialogues

The whole reported discussions and each single answer have been analyzed in terms of the previously defined parameters, summarized in Table 2. Table 3 reports the arising outputs for each test, whereas each value has been normalized with respect to the highest score obtained by the sample.

Student #	*Generalization*	*S-redefinition cycles*	*Correctness*	*Contradiction formalization*	*S-diffusion rate*
1	0,50	0,00	1,00	1,00	0,42
2	0,75	0,00	1,00	0,50	0,63
3	0,75	0,25	0,50	0,50	0,63
4	0,88	0,00	0,50	0,50	0,42
5	0,75	0,00	1,00	0,50	0,50
6	0,63	0,25	0,50	0,00	0,71
7	0,75	0,00	1,00	0,50	0,36
8	0,50	0,25	1,00	0,00	0,63
9	0,88	0,25	0,50	0,00	0,45
10	0,13	0,75	1,00	0,50	1,00

11	0,38	0,25	0,00	0,00	0,71
12	0,75	0,25	1,00	0,50	0,71
13	0,13	0,50	0,50	0,50	0,68
14	0,63	0,25	0,50	0,00	0,45
15	0,38	0,25	0,50	0,00	0,56
16	0,63	0,25	0,50	0,50	0,38
17	0,38	0,00	0,50	0,50	0,25
18	0,50	0,00	0,00	1,00	0,36
19	0,88	0,00	0,50	0,50	0,36
20	0,00	0,00	0,50	0,50	0,63
21	0,25	0,75	0,50	0,00	0,63
22	1,00	0,25	1,00	0,00	0,56
23	0,63	0,50	0,50	1,00	0,68
24	0,13	0,75	0,50	1,00	0,77
25	0,25	0,00	0,50	0,00	0,31
26	0,63	0,50	0,50	1,00	0,94
27	0,00	0,00	0,50	0,50	0,00
28	0,25	1,00	1,00	0,00	0,78
29	0,63	0,25	1,00	0,50	0,63
30	0,75	0,75	1,00	1,00	0,71
31	0,63	0,00	0,00	0,00	0,31
32	0,88	0,25	0,50	0,00	0,50
33	0,63	0,00	0,00	0,00	0,50

Tab. 3: Measures of the parameters characterizing the design discourse performed by a dialogue-based system, according to the proposed metrics.

4.3 Insights of the Analysis

The analysis of the illustrated outcomes, as summarized in Table 4, reveals at first that the prototype questionnaire is capable to support the reflections of a CAD user during embodiment design, since just few testers achieved a set of answers characterized by a very weak problem representation. With respect to the reported results concerning the *Correctness* parameter, the mean assumes the score 0,61 (thus the data are upwards unbalanced) and the value characterizing the first decile is already greater than 0. Moreover, the same factor presents a limited variability (the Relative Standard Deviation is about 50%, one of the lowest if the coefficients of the whole sample of parameters are compared), allowing to hypothesize that the dialogue system is capable to support the designer in articulating a structured and proficient design discourse. This results, on the basis of what has been exposed in 3.2, in a not negligible aid to individuate the right pattern for overcoming the conflicting requirements emerging during the embodiment design stage. Such statement is supported by the circumstance that almost all the students have individuated the eyelet as the element generating the undesired effect for the circular saw, regardless the position along the dialogue in which such aspect is underlined. The experimenters have thus identified the structural element of the designed system to be modified in order to fulfill the needs of any user of the product under development. As a consequence, also freshman designers owning outstanding individual skills, who would have autonomously individuated the core of the problem, have employed the proposed tool without misleading conclusions, while others have benefited from the questionnaire procedure.

The examination of the outcomes provides positive results also for the parameters named *Generalization* and *S-diffusion rate*, which show average values greater than 0,5 and thus a tendency to achieve good scores with reference to the treated variables. Moreover, the distributions of the values pertaining both the parameters present a reduced Relative Standard Deviation, hence a quite small variability. On the basis of the mutual links between the features of the design discourse and the characteristics of the problem solving procedure, the diffused emergence of positive scores for the discussed parameters determines a plausible capability of the dialogue-based system according to the flexibility of the tool with reference to different kinds of problems and technical contexts, as well as in terms of not losing sight of the system layout.

The residual parameters, i.e. *S-redefinition cycle* and *Contradiction formalization*, diffusedly show, on the opposite, low scores and high variability. On the basis of such outcomes, the main limitation of the tested question-answer interaction stands in the poor stimulation of the designer creativity and in the scarce efficiency of the problem solving approach. In order to enhance the current situation, specific measures have been attained with the aim of obtaining better performances with regards to these two parameters. According to the performed analysis, distinct measures have to be applied in order to achieve the expected improvements for such aspects, since the *S-redefinition cycle* and *Contradiction formalization* result completely unrelated, as resulting by the computation of the Pearsonôs coefficient for the distributions regarding all the surveyed parameters. According to the correlation indexes, the *Contradiction formalization* results weakly connected with any of the other issues, while enhancements in terms of the *S-redefinition cycle* could negatively impact the *Generalization* (the Pearsonôs coefficient is equal to -0,28). As a result, the definition of a new dialogue-based system has to be oriented with the highest priority towards the requested improvements, paying attention not to jeopardize the capability of the tool to provide more abstract representations of the problem. Within the support of CAD systems for embodiment design, the sequence and the content of the questions should be addressed to allow a quick contextualization of the ideas emerging at a more abstract level.

	Generalization	*S-redefinition cycles*	*Correctness*	*Contradiction formalization*	*S-diffusion rate*
Mean	0,54	0,26	0,61	0,39	0,55
Standard deviation	0,28	0,28	0,32	0,37	0,20
Relative Standard Deviation	51,1%	109,8%	53,6%	93,9%	37,2%
First decile	0,13	0,00	0,10	0,00	0,32
Last decile	0,88	0,75	1,00	1,00	0,76
Correlation with S-redefinition cycles	-0,28	-	0,25	0,08	0,71
Correlation with Correctness	0,15	0,25	-	0,16	0,28
Correlation with Contradiction formalization	-0,06	0,08	0,16	-	0,13
Correlation with S-diffusion rate	-0,08	0,71	0,28	0,13	-

Tab. 4: Main indexes to summarize the results of the analysis in terms of the adopted metrics to characterize the design reasoning.

5 CONCLUSIONS

The main achievement of the paper stands in the profile for a prototype version of a dialogue-based system to be implemented within a CAD environment to support users along the crucial activities carried out within embodiment design. A preliminary testing campaign allows to individuate with a good confidence level the major strengths and weaknesses of the proposed questionnaire, as reported in Section 4. However, in order to increase the reliability of the results, a planned activity stands in administering a sample of freshman designers, constituting a control group, the task of elaborating a design discourse about the same case study and without the employment of the question-answer support. The authors are indeed unaware of any research to be compared against that describes experiments of design protocol analysis concerning the embodiment phase.

The fine-tuning of the proposed question-answer technique, beyond establishing the most suitable sequence for problem setting and solving, is expected to observe two development steps. The first implementation in a software environment can be seen as a support to stimulate the display of design annotations, which are deemed to both aid the individual design reasoning and enforce the collaborative design tasks [26]. A final version of the CAD application will be constituted by a dialogue interface capable to coordinate the iterations between conceptual and embodiment design, speeding up the selection of the most appropriate tools according to the kind of encountered problems and allowing the link between different design environments.

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