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INVESTIGATING ON THE RE-USE OF CONCEPTUAL DESIGN REPRESENTATIONS

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Abstract

Systematic conceptual design approaches foresee the realization of abstract representations, according to their specific formalisms and rationales. Therefore, even if not explicitly conceived for this purpose, they implicitly allow to store information about the explored design space. Unfortunately, the effectiveness of the re-use of the recalled representation is unclear, especially if reused by designers not comprehensively learned about the original method. This paper shows an experimental investigation on this argument, where a sample of thirty-five MS engineering students is involved.

Keywords: conceptual design, engineering design, design knowledge, design representations, design creativity

1. Introduction

Besides the documentation resulting as the output of the different product development phases (technical specification, drawings, reports, manuals etc.), design activities also produce a large quantity of documents that embed knowledge potentially reusable in future projects. Indeed, the increasing attention to innovation implies the continuous evolution of design requirements with consequent re-design activities devoted to bring upgrades and improvements. Therefore, the information about the explored design alternatives, the reasons behind the design choices and about the explored design space, should be made comprehensively and rapidly available to designers. In other words, a complete accessibility to the knowledge acquired during past design processes is crucial to avoid useless effort repetitions, and to allow more rapid design improvements.

Currently, technical reports constitute the most diffused way for archiving the recalled set of information, but unfortunately they seldom provide a comprehensive mapping of the design path followed to obtain the preferred concepts. As a direct consequence, when a designer is asked to work on a product previously designed by someone else, he/she inevitably needs to spend a lot of time for extracting information about the fundamentals of the system and the reasons behind certain decisions.

Systematic conceptual design methods are based on a set of abstract representations containing explicit information about the functionalities and the working principles characterizing the devised concept, e.g. those based on Functional Decomposition and Morphology (FDM) (Eppinger and Ulrich, 2007; Pahl et al., 2007; Ullman, 2010). Although not explicitly conceived for archiving purposes, the recalled schematic representations contain information about the knowledge developed and/or exploited by designers. Accordingly, it is acknowledged in literature that abstract representations like functional models can be used for storing design information (Atilola et al., 2015). In fact, several researchers have studied the use of design representations as stimuli on design outcomes (Goldschmidt and Sever, 2011; Atilola and Linsey, 2015; Atilola et al., 2015). Among the others, Linsey et al. (2008) evaluated the effect of FDM functional structures in a design-by-analogy experiment, concluding that the adoption of

the recalled representations could enhance design processes. However, no specific studies have been published about reusing representation sets coming from a precedent application of conceptual design approaches produced by other designers.
Unfortunately, it is acknowledged that academic methods are not widely diffused in industry (Tomiyama et al., 2009). Consequently, a further open issue concerns the re-usability of archived conceptual design representations produced with structured approaches, whatever is the specific degree of education that the current designer has on those methods. With the aim of contributing to the research in this context, in this paper we intentionally consider the case where designers are unlearned about the method from which representations have been originally generated.
Since design representations strictly grounded on the concept of function suffer of the multiple interpretations that designers give to function (Eckert et al., 2011; Vermaas and Eckert, 2013), we decided to consider an additional representation set for our investigation. The additional representation here selected derives from the so called Problem-Solution-Network (PSN) approach (Fiorineschi et al., 2016), which is claimed to overcome some of the FDM limitations highlighted in literature. The main reason behind this choice, is that although PSN representation is sensibly different from FDM, the grounding method preserves some peculiarities of the FDM approach, e.g. the main design problem decomposition and the morphological composition of different solution variants. Therefore, we decided to use both FDM and PSN representations in an experimental test where designers are involved in a redesign activity, starting from results achieved in precedent design sessions. More precisely, we aim at answering the following key question: do designers, even uneducated about conceptual design methods, benefit any creativity advantage by the availability of abstract design representations produced by others?
The paper describes an experiment aimed at answering the above research question and is structured as follows: Section 2 introduces the selected representation models and adds some considerations about the limitations of the choice we made. Section 3 describes the assumptions and the set-up of the design experiment. Experimental results are shown in Section 4, and related discussions in Section 5, together with further considerations about future research and practical implications. Eventually, the last section summarizes the conclusions of this work.

2. Considered representations

This section briefly describes the design representations considered for this investigation, with the intent of providing the fundamental information for the comprehension of the paper. Moreover, some considerations are reported, concerning the expected limitations of the work.

2.1. FDM representation set

Among the conceptual design methods coming from academia, it is largely acknowledged the so-called Functional Decomposition and Morphology (FDM) approach (Pahl et al., 2007), where functional models and related morphological matrices constitute the two graphical representations of the related formalism. FDM is a systematic conceptual design approach strongly based on the concept of "functions", intended as transformations of one or more Energy-Material-Signal (EMS) flows. More precisely, functional models constitute the main abstract representation, where the functions and their EMS relationships are represented by black boxes (functions) connected with specific arrowed lines (representing the EMS flows).
Once a function structure is generated, it constitutes a sort of platform for generating overall concepts. More specifically, different possible solutions are identified for the implementation of each sub-function, and schematic representations of them are listed in a graphical tool, i.e. the “morphological chart” (Pahl et al., 2007) or “morphological box” (Heller et al., 2014), derived from the so called morphological approach (Zwicky, 1969). In this way, different combinations can be evaluated, within the variety of solutions found for implementing each single sub-function.

2.2. PSN representation

The PSN is a systematic approach conceived to support the designer during the conceptual stage, which is subdivided in three main phases, i.e. the Concept Generation, the Concept Composition and the

Concept Selection (Fiorineschi et al., 2016). In the first phase, the overall design problem is decomposed in a network of problems and solutions, hierarchically organized according to the related levels of abstraction. More specifically, different solution variants can be generated for each problem, each of them potentially generating one or more additional sub-problems to be solved, and so forth.
The network is intended to be built by following a set of six rules, which provide detailed indications about how to proceed with the formulation of problems and the related solutions. Specifically, problems are formulated in the form of questions such as "How to *verb – noun*?" related to the delivery of functions, system qualities, properties or performances.
In the second phase, different solutions combinations (i.e. different PSN ramifications) are evaluated in order to obtain different overall concept variants. In this step, the network acts as a morphological tool where different solution variants are listed for each problem, by following a problem-solution co-evolutionary relationship from higher abstraction levels to lower ones.
Eventually, similarly to FDM, concept variants are selected through classical processes acknowledged by literature, e.g. the "Concept selection matrix" (Pugh, 1991), "Selection charts" (Pahl et al., 2007) or QFD-like matrices (Akao, 1990).

2.3. Limitations imposed for the experiment

Both PSN and FDM representations allow to keep track of the different solution variants for each single problem or function to be implemented. Therefore, they offer the opportunity of reusing also design efforts spent for un-preferred solutions. However, in this paper we decided to focus only on the representation of a single concept (i.e. a single set of ramification in the PSN and a single EMS structure equipped with a single-column morphological chart). The reason behind this decision resides in the different expansion that the two considered representations may go through, depending on the concept variants to be represented. More precisely, while PSN allows to add an indefinite number of additional ramifications on the same network (mainly expanding horizontally) independently on how sub-functions interact with each other, differently, FDM may need the realization of a different number of function structures, each of them linked to a specific morphological chart. Indeed, different concepts may consider different EMS flow variants (e.g. different types of energy), potentially leading to different sub-functions and then different function structures.
Moreover, both the methods foresee an evaluation phase where important information about decisions behind concept selection is registered in matrices or charts (e.g. Pugh, 1991) or Eppinger and Ulrich (2007). Nevertheless, the information related to the evaluation phase is not considered in this experiment and thus not provided to the subjects of the experiment.

3. Set-up of the design experiment

This section provides a detailed description of the investigation method with details on the considered sample of convenience, the testing procedure and the metrics adopted for performing the required assessments.

3.1. Sample of convenience

Despite it would be useful to involve expert practitioners in this experimental activity, we decided to make a first test with engineering students to start gathering some evidences to answer the research question. Nevertheless, the involvement of Master of Science (MS) students ensures a certain degree of acquaintance with the design practice.
More in detail, the experiment involved the participation of thirty-five MS students enrolled in the Mechanical Engineering study programme, 2nd year. The experiment was carried out just a couple of weeks after the start of the semester, i.e. before introducing any model about the representation of conceptual design information, including FDM and PSN. This was intentionally made according to the research question.
We divided the sample of students in three different groups: two of them devoted to the exploitation of the two (one per group) investigated representations (namely PSN and FDM groups), while the third group (EXP group) was considered as a control group. More specifically, we substantially administered

a "placebo" to EXP group, by providing them a technical drawing of the starting product, i.e. only standard-type representations of technical information.
Being the sample not so numerous, we opted for making the students work individually, so as to have statistically meaningful data to perform the analysis.
For organizational issues, students turned up to be divided not evenly in the three groups, and specifically 13 students fell into the EXP group, 10 and 12 in the FDM and PSN groups respectively.

3.2. Testing procedure

In order to evaluate the effect of the two design representations, the proposed testing procedure consists of two distinct phases. The first one is intended to provide initial and neutral information about the sample of convenience. More specifically, we expected to extract sufficient data to determine the starting characteristics of each group (according to the adopted metrics), in order to successively assess the impact derived from the introduction (in the second phase) of the investigated modelling approach. Accordingly, in the first phase, we provided the same material to all groups, containing the graphical (Figure 1) and textual description of the design task (156 words), together with a short textual description of a common ball-point pen (271 words). The full version of the recalled material is available on: https://goo.gl/Zd2LeX.

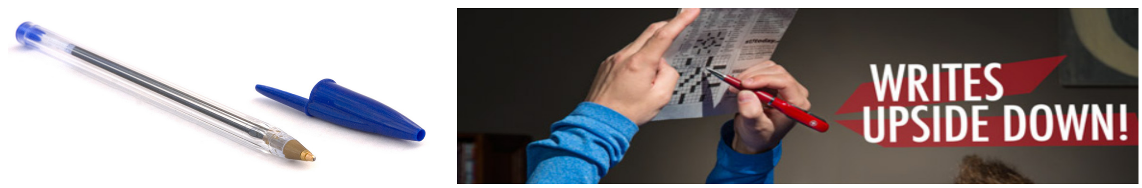

Figure 1. Images provided in the task description

The design task, the same across the two phases, was focused around the problem of "writing upside-down", i.e. around the problem derived from the negative action of Gravity on the fluid ink when the pen is overturned. We selected this specific task, since it is reasonable to assume that each subject had the same familiarity with pens and with the recalled problem. Moreover, we also assumed that the difficulty level of the task could be considered congruent with the limited design experience of the sample and with the available testing time.
In the first round, the students were asked to conceive the highest number of ideas, in a limited time of 25 minutes, by providing both graphical (sketches) and short textual descriptions of the devised concepts. For this purpose, we also provided an "unlimited" set of paper forms (available on: https://goo.gl/p1JFE8) where students could record their ideas.
At the end of the first phase, we collected the produced concepts and distributed additional material to groups. In this second test phase, each student received a paper sheet with the information structured according to the group he/she belonged to. More specifically, subjects belonging to the EXP group received the exploded view drawing and the bill of material of a common ball pen. Subjects of the FDM group received the corresponding model describing how the same ball pen works (EMS functional structure and the related morphological chart). Similarly, PSN students were provided with a network of problems and solutions describing a possible logical flow to explain the current design of the ball pen. The different information sheets provided to the three groups of treatment are depicted in Figure 2, but can be found with full readability on: https://goo.gl/SUR1Ca.
Each student was asked to conceive additional ideas as much as they could, but trying to exploit the additional information provided with the received information sheet. Also in the second phase, the time was limited to 25 minutes, still with virtually unlimited forms for representing the generated concepts.

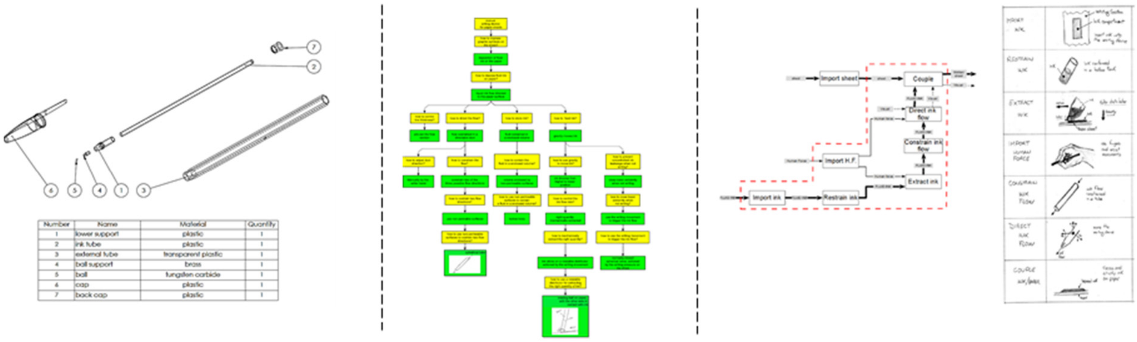

Figure 2. Overall view of the supplemental material provided in phase 2, respectively for EXP, PSN and FDM groups (high quality images available on https://goo.gl/SUR1Ca)

3.3. Evaluation procedure

In order to assess the ideas produced by the testers, and then to evaluate the impact of the different representation schemes, we referred to acknowledged literature metrics based on the assessment of the quantity, quality, variety and novelty of ideas (Shah, 2003), and considering only the new functional requirement requested in the design brief. For verifying the statistical reliability of the differences observed among the two phases, within each group we performed (where possible) the t-test for paired or dependent samples (Sheskin, 2003) on the specific parameter values. A single evaluator performed the assessment, after a comprehensive alignment session with other two evaluators (on a 15% of the whole sample).

After introducing the recalled metrics, the following paragraphs provide a detailed description of the way we applied them.

3.3.1. Quantity

For assessing this parameter, we simply counted the number of ideas conceived by each subject, in each group, and in each phase. Then, we calculated the "mean quantity for group" (Qn), for each group and each phase, by referring to Equation 1:

$$Qn = \frac{n_{id}}{n_{st}} \tag{1}$$

where, "n_{id}" represents the total number of ideas conceived by a specific group in a specific phase, and "n_{st}" represents the number of subjects for the considered group. We used this metric instead of the simple "total number" ideas as suggested by Shah et al. (2003), because of the different size of the three groups. By means of Qn, the "quantity" parameter can be evaluated independently from the actual number of participants.

3.3.2. Quality

Since the students generated their concepts without a detailed design specification, it was not possible to check the fulfilment of design requirements of all proposed concepts. We'd rather assessed the quality of the ideas proposed by participants, by judging their feasibility and viability. We limited the assessment to a four-level scale, where the lowest level (1) corresponds to "unfeasible and/or not working" solutions, the second level (2) to "likely not feasible and/or not working", the third (3) to "likely feasible and/or working" and eventually, the fourth "(4), to "feasible and/or working" solution. However, similarly to the previous parameter, we needed to compare the values independently from the group numerousness. Therefore, after the recalled four-level scores had been assigned to each idea, the "mean quality for group" (Q) was calculated with Equation 2, for each group and for each phase:

$$Q = \frac{\sum_{i=1}^{n_{st}}\left(\frac{\sum_{j=1}^{m} q_{ij}}{m}\right)}{n_{st}} \tag{2}$$

where, "n_{st}" is the same of Equation 1, "m" is the number of ideas conceived by a specific subject in a specific phase, and "q_{ij}" is the quality score assigned to the specific idea. In this way, the parameter is independent from both the number of subjects and the number of conceived solutions.

3.3.3. Variety

This parameter has been assessed as originally proposed by Shah et al. (2003), considering a single function (deposing ink while writing upside down) and a single design stage (conceptual), but without considering the lowest hierarchical level, i.e. detail variations. Such a decision is a direct consequence of the limited detail level of the conceptual solutions requested in this test.
Therefore, Equation 3 has been used for calculating the Variety score of each group for each of the two testing phases:

$$V = \frac{10 \cdot n_{pp} + 6 \cdot n_{wp} + 3 \cdot n_{str}}{n_{id}} \tag{3}$$

where, "n_{id}" is the total number of ideas for the specific group in the specific phase, "n_{pp}" is the number of the observed physical principles variants, "n_{wp}" is the number of the observed working principles variants, and n_{str}" is the number of the observed main structure variants.

3.3.4. Novelty

For this parameter, we considered the "a-posteriori" knowledge approach originally proposed by Shah et al. (2003), but with some differences. Indeed, they refer to the identification of common "key attributes" across the entire set of ideas, in order to identify how they have been implemented in each idea. Moreover, they also assign different weights for taking into consideration the related importance levels. However, it was extremely difficult for us to identify such a set of common attributes, because of the high number of examined ideas and the related high heterogeneity.
To overcome such a problem, we took inspiration from the novelty assessment proposed by Sarkar and Chakrabarti (2011). More specifically, we referred to the different "novelty rates" that depends on "where" the differences could be observed in relation to a reference product or systems (i.e. very high novelty if there are different functions, high novelty if physical effects, state change and organs are different, and so forth up to the lowest novelty rate). However, since we adopted "a-posteriori" evaluation, it was not possible to identify such a reference product.
Nevertheless, we inferred that different weights could be assigned depending on the item, i.e. physical principle (PP), working principle (WP) or structural (STR), where the differences have been be observed. As a consequence, referring to Shah et al. (2003), we calculated the "a-posteriori" novelty score for each item (PP, WP and STR) for each group in each phase (Equation 4).

$$N_i = 10 \cdot \frac{n_{id} - I}{n_{id}} \tag{4}$$

where "N_i" is the novelty score associated to a specific item "i" (PP, WP or STR) for a specific group in a specific phase, "n_{id}" is the total number of ideas generated by the testers belonging to the group , and "I" is the count of the occurrences of the specific item variant in the same group. For assessing novelty scores, the universes of solutions have been considered as independent between groups, allowing to easily evaluate how much the introduced representation affects the design outcomes of the same group of students. Moreover, the recalled universes have been considered as incrementally expanding from the first to the second phase. Therefore, for each group, the novelty scores assessed in phase two, take into consideration the sum of the ideas proposed across the two phases, but are calculated only on the concepts generated in that phase.
Then, with Equation 5 we assessed the novelty scores for each idea, by taking into consideration the novelty scores of the items characterizing the solution (as previously identified in the Variety assessment), and the related weights. The latter have been obtained by the normalization of the three weights considered in Equation 3, i.e. 10 for PP, 6 for WP and 3 for STR.

$$N = 0{,}53 \cdot N_{pp} + 0{,}32 \cdot N_{wp} + 0{,}16 \cdot N_{str} \tag{5}$$

Eventually, for each group and for both the testing phases, we calculated the "mean novelty", i.e. the mean value of the novelty calculated across all ideas within a group, to observe the overall behaviour of the investigated sample of convenience across the two phases.

4. Results

At the end of the test, participants sketched a total number of 160 ideas, two of which, have been represented in Figure 3 to provide reference examples for the reader. Moreover, besides sketches, students provided few lines of textual descriptions (not reported here) in order to explain the functioning of each proposed idea.

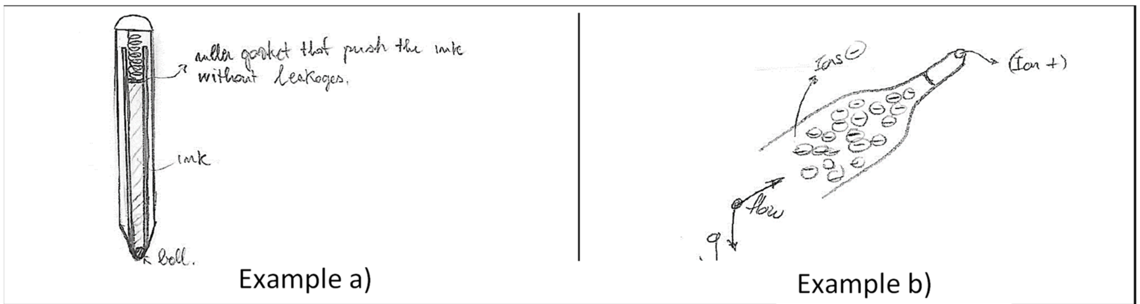

Figure 3. Two examples from the set of ideas produced by the test subjects

4.1. Quantity

Concerning the quantity of proposed ideas, for all groups we observed a sensible reduction from the first to the second phase. In Figure 4, it is possible to observe the entity of the recalled difference, together with the different behaviours observed for the examined groups. The limited samples size for each group and the presence of some non-normal distributions may lead to a poor reliability of the t-tests. However, the latter have been performed for a first evaluation, and as shown in Table 1, it is possible to observe that assuming a reference p-value of 0,05, apparently meaningful differences within groups seems to exist. Figure 4 also shows different trends among groups. More specifically, the FDM group registers a diminution almost 20% higher than EXP group, while the PSN one registers a diminution that is even twice than EXP.

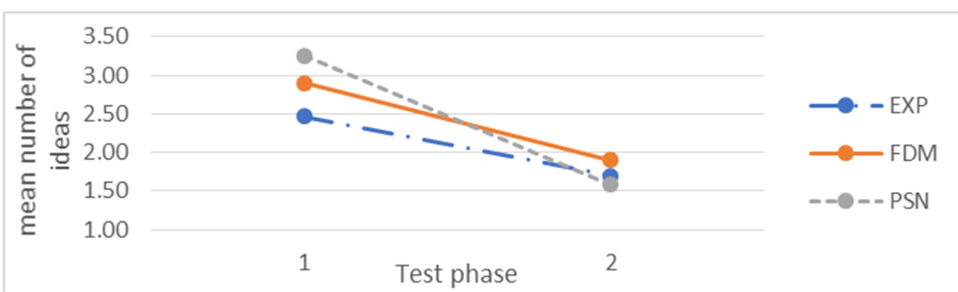

Figure 4. Reduction of the mean number of ideas observed between the two test phases

Table 1. Differences between the two phases and related p-values for t-tests performed on the mean numbers of ideas generated by examined groups

Group	EXP	FDM	PSN
Difference	0,77	1,00	1,67
p-value	0,006	0,048	0

Overall, the three groups behaved quite differently in the first round, revealing an unexpected heterogeneity. Besides, higher differences in terms of quantity of generated ideas were recorded for the group which generated the biggest amount of concepts in the first round.

4.2. Quality

In order to provide a reference for the reader, we report that the two examples shown in Figure 3 have been assessed with the highest and the lowest quality level (examples "a" and "b" respectively). In the first case, notwithstanding the limited detail level of the concept representation, we didn't find any limitation to the development of a pen based on that concept.
For the second idea, instead, we encountered many doubts concerning its actual viability. Indeed, even assuming the feasibility of a fluid ink charged with or made by "negative ions", we considered not adequate the attraction of the positive charge of the ball tip so as to be capable of overtaking gravity, but at the same time not limiting the output flow of the ink once reached the tip.
All ideas were processed according to the judgment criteria illustrated above, revealing that for EXP and PSN groups, quality remains practically unchanged between the two phases of the test. Diversely, it has been observed a certain reduction for FDM group, registering a difference of 0,76 points, i.e. a reduction of 28,3% from Phase 1 to Phase 2 (Figure 5). Such difference has been statistically validated through a paired t-test, with a p-value of 0,032. However, it is worth to notice that limited sample size may imply a limited reliability for t-tests.

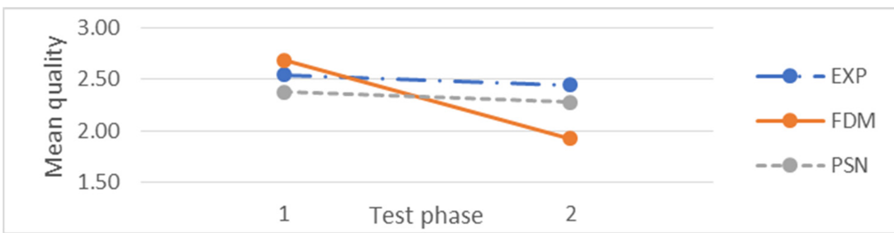

Figure 5. Reduction of the mean quality of ideas observed between the two test phases

4.3. Variety

According to the variety metric introduced in Section 3, physical principles, working principles and (rough) embodiment characteristics have been extracted from the set of concepts proposed by students. The number of different observed items is listed in Table 2.

Table 2. Observed items variety

	EXP		FDM		PSN	
Phase	**I**	**II**	**I**	**II**	**I**	**II**
PP variants	6	3	6	6	7	6
WP variants	12	8	12	10	15	11
STR variants	24	16	17	15	26	18

To show how the numbers listed in Table 2 have been obtained, we report here the way we assessed the examples reported in Figure 3. More specifically, Example "a" has been coded with a "liquid in pressure" physical principle, a "moving surface (or piston)" working principle and a "coaxial spring" as the main embodiment characteristic. Differently, Example "b" has been coded with a "Electrostatics" physical principle, a "electrostatic attraction between ionized ink and tip" working principle, and a "ionized fluid ink" as the main structural characteristic.
The assessment of the variety level of the proposed ideas, shows a non-negligible effect of the introduction of abstract formalisms (PSN and FDM). Indeed, differently from EXP group, where the introduction of the related supporting material does not bring any meaningful variation, subjects stimulated with FDM and PSN models recorded a similar positive variation (Figure 6 and Table 3). To a certain extent, PSN group reached a higher increment if compared with the FDM one.

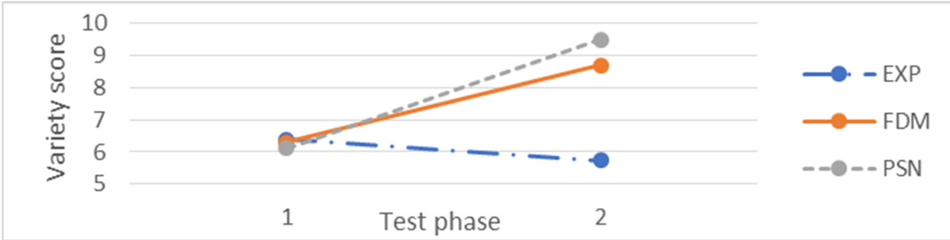

Figure 6. Variety observed for groups between the two test phases

Table 3. Variety differences for groups, between phase 1 and 2

Group	EXP	FDM	PSN
Difference	-0,64	2,38	3,37

4.4. Novelty

Before showing these results, we report two illustrative examples of novelty assessment. Still referring to Figure 3, we obtained the results shown in Table 4. The physical principle used in Example "a" has been proposed quite often within the specific group, and due to the weights introduced in Section 3, it leads to a low novelty score. Differently, Example "b" is based on extremely original items (for the specific group and phase), and then, a relatively high novelty score has been assigned.

Table 4. Novelty assessment for examples of Figure 3

Example	a	b
Physical principle score	2,50	9,66
Working principle score	6,56	9,66
Embodiment variants score	8,44	9,66
Novelty score	4,72	9,66

By applying the novelty metrics introduced in Section 3 on the sample of concepts produced by the students, we observed again a significant heterogeneity between groups. More precisely, as shown in Figure 7, an offset can be easily noticed for values related to PSN group. Nevertheless, the trend from the first to the second test phase is practically the same for all the considered groups (see also Table 5), i.e. no statistically reliable difference can be observed between the two phases. It is important to notice that the limited sample size and an observed non-normal distribution of novelty results, implies a poor reliability of the t-test. However, as visible in Figure 7, the t-test is used here only to further confirm the absence of any reliable difference among the two phases.

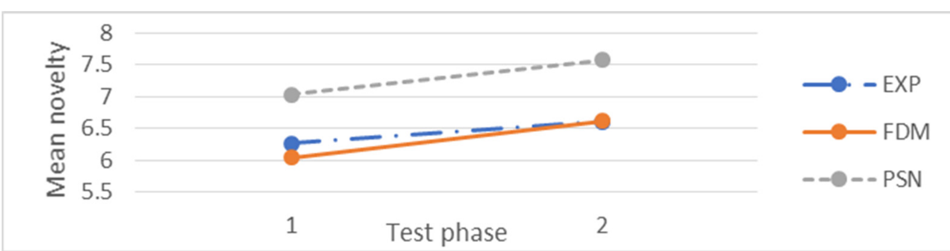

Figure 7. Mean novelty scores observed for groups between the two phases

Table 5. Differences and related p-values for t-test performed on the mean novelty observed for ideas generated by examined groups, between phase 1 and 2

Group	EXP	FDM	PSN
Difference	0,33	0,58	0,54
p-value	0,494	0,352	0,283

5. Discussions

In this section, we discuss the results shown in Section 4: potential practical implications of the observed results are highlighted, together with considerations about the limitations of the work and future research developments.

5.1. Discussing about results

Concerning the quantity of proposed ideas, it is difficult to draw definitive conclusions. Indeed, even if it is expected that the number of generated solutions gets smaller and smaller in time (Howard et al., 2010), we actually do not known how this trend is related to the proposed design task, to the level of design expertise of the subjects and/or to the provided information support tools. However, we can observe that the three different modelling schemes almost led to the same effects. Therefore, it is possible to assert that, within the design situation simulated during the test, investigated representations do not bring any measurable effect in term of quantity of devised ideas with respect to detailed technical drawings. The more evident (not validated) negative effect observed in the PSN group cannot be explained here. Indeed, it can be assumed that "reading and understanding" the contents of each problem and solution boxes could have consumed most of the available time for the subjects. However, this remains a conjecture, because we have no data to validate such a hypothesis.

The negative effect observed on the quality parameter with the FDM formalism (if validated) could somehow be explained with the limited expertise that the subjects had about reasoning in terms of functions. As already mentioned in Section 2, it is well acknowledged in literature that talking and reasoning in terms of functions is not a trivial task. Therefore, it is possible to infer that the lack of comprehensive instructions about how to interpret the FDM functional model and the related morphological matrix, led students towards more "confused" ideas in terms of feasibility and viability. Moreover, the quality assessment has been performed by using an ad-hoc metric conceived for this particular work, and then should be repeated by considering other literature metrics (e.g. that of Linsey et al., 2011 or that of Berthelsdorf et al., 2016).

Results represented in Figure 6 show that the introduction of the abstract modelling schemes brought a significant improvement of solutions variety, while technical drawings introduced a certain fixation. Several hypotheses could be formulated about the reason of this result, and one of them is the probable de-fixating effect derived from pushing students to think more abstractly with FDM and PSN models. Accordingly, other studies show that functional models do not tend to cause design fixation (Atilola et al., 2015), as well as that more ambiguous stimuli tend to be less fixating (Howard et al., 2009). Overall, the results here presented show that also the co-evolutionary problem-solution logic behind the PSN formalism can lead to the same positive results that can be reached with FDM, however we still have no means to claim whether the positive impact observed on Variety can be directly correlated with de-fixating effects of PSN and FDM.

Concerning novelty, results presented in Section 4 show that the mere introduction of abstract formalism actually does not bring to any valuable effect. It means that even pushing students to think more abstractly with PSN and FDM models, it has been not sufficient for generating solutions that are more "unusual", in relation to the considered universes.

5.2. Practical implications

The results discussed in this section show that the introduction of the investigated representations in the second phase of the test, somehow led to non-negligible advantages in terms of variety of proposed ideas. Such an observation could support the diffusion of systematic design methods, since it further justifies the effort needed to construct the related representations. Generally speaking, any scientifically valid and concrete proof about evident advantages is certainly useful for "convincing" designers (and even students) that the time spent in learning systematic methods is a good investment. In this specific case, if results about variety will be confirmed in future research activities, it would be possible to assert that the efforts spent in realizing the schematic representations foreseen by systematic methods, "at least" sensibly and positively support the variety of concepts generated in successive re-design activities, even if used by designer un-learned about the methods.

5.3. Further limitations and research hints

The achieved results constitute the grounding for future research activities, aimed at better understanding the impact of representations coming from conceptual design methods. Validating the results with further similar testing activities certainly constitute a necessary action. Nevertheless, some limitations can be ascribed to the work presented here, and overcoming them is another important research direction. Indeed, the sample size for each group is quite limited and sometimes data do not follow a normal distribution. Therefore, besides the lack of information concerning the trends observed with the "quantity" parameter and the insensitivity of the novelty scores, we also need to better investigate about negative effect of FDM representation on the "quality" parameter. Moreover, the work presented in this paper has not investigated in detail the impact of the proposed modelling schemes on "design fixation" effects (Purcell and Gero, 1996). To this purpose, an immediate step is to further analyse the available data, also considering those obtained in a supplemental "third phase", already performed but not shown here. In such a phase, performed immediately after the end of the second one, further 25 minutes have been assigned to the same sample of students, with the additional "explicit suggestion" of trying to conceive other solutions, not limiting to the ball-tip for distributing ink. By analysing data across the three phases, we aim at further observing the trend shown in this paper, and also to study possible effects of representations in terms of design fixation (e.g. by counting the solutions not considering the ball, across the three phases). Moreover, the limitations imposed to this investigation (see Section 2) neglected to consider the capability to represent more design alternatives in the same schematization. As already mentioned, also the effects caused by the different expansions of the representations should be investigated comprehensively. Furthermore, it could be interesting to evaluate the effect of representations from creativity-enhanced FDM versions (Fiorineschi et al., 2018). Eventually, a limitation of the present work is that a single evaluator performed a single round of assessments for this preliminary version of the research analysis. Although, it has been performed after a comprehensive alignment session with other two evaluators), and although we are confident about the assessments shown in this paper, an inter-rater reliability with (at least) an additional evaluator should be performed to comprehensively validate the results.

6. Conclusions

The work presented in this paper concerned an experimental investigation on the reuse of information contained in representations coming from systematic conceptual design methods. The test has been performed on a sample of convenience constituted by thirty-five MS mechanical engineering students, (2nd year) and two different modelling schemes have been tested across two design sessions, each of them lasting 25 minutes. At the end of the test, 160 different ideas have been generated, and successively assessed with a metric based on four parameters, i.e. quantity, quality, variety and novelty. Observed results showed that the models characterized by an abstract representation of design-related information led to non-negligible advantages in terms of variety of solutions. Concerning the quality parameter, in this paper assessed in terms of expected viability of the generated concepts, we observed a negative effect for one of the investigated representations, but further and more detailed analysis should be performed before confirming this preliminary observation. For example, the same set of solutions should be assessed with other metrics to be identified among those available in literature. In this way, it would be possible to confirm or deny the results observed here about quality.

Moreover, the experiment concerns a very simple device to be designed, but it is necessary to perform tests also on more complex products to evaluate the impact of product complexity on the reuse of abstract representations. Eventually, some other limits have been ascribed to this work by authors themselves and, accordingly, future research developments have been suggested. In particular, one of these future directions is the exploitation of additional data obtained from a supplemental third testing phase, to further analyse the observed trends and to possibly evaluate design fixation effects.

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