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A-Posteriori Novelty Metrics Based on Idea Decomposition

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Novelty assessment procedures based on a-posteriori rationales are often used to extract useful information about creativity and/or idea generation effectiveness. In this context, the metric proposed by Shah and colleagues in 2003 (SNM), is one of the most used in design research. However, scholars highlighted some non-negligible flaws and also possible variants have been proposed, claimed to improve the original version. The aim of this paper is to perform a systematic literature review about the SNM variants, in order to verify whether the acknowledged flaws of the metric have been overcome or not. As a result, this paper highlights that the problems affecting the original SNM version have not been comprehensively resolved, and the different variants proposed in literature can even present some additional flaws. Accordingly, a comprehensive list of pros and cons of the reviewed metrics has been reported, thus providing fundamental information to support accurate metric selection.

Keywords: Novelty; Novelty assessment; Creativity; Idea infrequency; Idea uncommonness.

1. Introduction

Creativity is the current lighthouse for many scholars involved in design-related studies, and one of its most important parameters that underpins the plethora of different definitions is the “novelty”. According to the available literature, the latter can assume different meanings (e.g. technological novelty [91], historical novelty, psychological novelty [8], unexpectedness [87], etc.) that depend on the parameters on which the assessment is performed, and, more importantly, on what is considered as the reference to establish what is novel or not. A quite simple distinction was made by Shah, Vargas-Hernandez and Smith [74], who identified two distinct families of novelty assessment approaches, i.e. the "a-priori" or the "a-posteriori". In the first case, it is necessary to identify a reference solution (or a reference set of solutions) to discover whether the examined ideas are more or less novel, while in the second case the set of ideas to be assessed constitutes the reference itself. In this way, it is possible to count the occurrences of similar ideas generated in the same design or idea generation session. Therefore, by following a-posteriori approaches, novelty is intended as a measure of the unusualness, uncommonness or infrequency of a specific idea in relation to the same group of ideas (e.g. arisen from the same experiment), thus implementing the concept of psychological novelty (i.e. what is novel for the individual or groups of individuals that generated the idea). Although idea infrequency is relative to a specific set, it can be extremely useful for experimental purposes, since it allows to assess the effects of administered treatments (e.g. stimuli, incubation, methods, etc.), and to avoid the identification of an external reference. Indeed, the latter is one of the most critical issues of a-priori approaches, which implies to carefully select the reference by performing comprehensive investigations about the background of the considered sample of subjects involved in the experiment.

A-posteriori novelty metrics are often used or referenced in design research (e.g. [5, 41, 42, 48, 52, 55, 89, 94, 96, 100]) and the metric of Shah, Vargas-Hernandez and Smith [74] (hereinafter called SNM), is one of the most largely used and acknowledged among design researchers, as confirmed by the high number of citations on Scopus (610 at October 2019). However, besides the relativeness of metrics based on infrequency, scholars recently highlighted some additional flaws of SNM (see Section 2) and proposed some upgrades or variants with the aim to overcome them. Unfortunately, very often these variants have been proposed and applied on specific experimental cases, without providing the information required to perform comprehensive discussions about their actual reliability and general validity/applicability. Indeed, due to the acknowledged pros and cons of SNM, scholars involved in design experiments can feel the need to identify the most effective SNM variant and/or to understand their actual advantages among those claimed for the proposals available in literature. In other words, it can be difficult for researchers to orient through the different variants proposed for SNM because only few contributions citing the work of Shah and colleagues [74] really refer or can be attributed to a SNM variant. Moreover, the identification of the related pros and cons is not a trivial task.

Consequently, the objective of this paper is to review systematically the SNM variants available in literature to understand whether the acknowledged issues about SNM have been resolved or not. Accordingly, the following research hypothesis is formulated and investigated through this work:

HP: After many years of SNM-related studies, the issues concerning the application and the interpretation of the SNM-based metrics have been resolved.

Section 2 reports a short background about the role of novelty in creativity studies, also introducing the original version of SNM. The research approach used to perform the literature review is described in Section 3, while the outcomes are presented in Section 4. In particular, besides a short introduction to the considered contributions, a comprehensive description of their criticalities is reported. In Section 5, the most relevant problems of the reviewed metrics are explained, while Section 6 is dedicated to the discussions. Section 7 shortly resumes the achieved results, and Section 8 is dedicated to Conclusions. Eventually, the last section reports both the limits of the work and the expected impact.

2 Background

The concept of creativity is one of the most important research arguments in design-related studies, since it is acknowledged to deeply influence the generation of new products and processes, business [14, 15, 45, 47], and innovation [68]. Accordingly, non-negligible research efforts have been spent to support, assess and/or understand creativity (e.g. [13, 19, 102, 27, 31, 36, 37, 66, 68, 69, 90]). As a consequence, a plethora of design methods and tools (e.g. [2, 3, 12, 18, 25, 51, 56, 60, 75, 76]), different definitions of creativity [67, 70] and related metrics (e.g. [50, 54, 59, 90]) can be found in literature.

Among the different definitions, Torrance [83] introduced "fluency" and "flexibility" to describe creativity, while Amabile [4] considered two additional dimensions to assess creativity, i.e. "elaboration" and "originality". Another multidimensional definition of creativity is that of Cropley and Cropley [21], who define creativity in terms of "relevance", "novelty", "elegance", and "generalizability", while Sääksjärvi and Gonçalves recently added the concept of "meaning" [64]. Creativity has been also expressed as the ability to consider different problems' perspectives to generate novel potential solutions [53]. Additionally, Weisberg [98] defined creativity with the terms "novel" and "valuable". Generally speaking, it is possible to assert that scholars agree on the two creativity dimensions of "novelty" and "usefulness" (e.g. [1, 16, 67, 68]). In particular, according to Chiu and Shu [16], the novelty dimension can be expressed in terms of newness, originality or surprise, while usefulness is often considered in engineering literature in the context of functionality [61, 85]. Creativity is also considered (and assessed) by Shah and colleagues in terms of idea generation effectiveness, by considering four different dimensions, i.e. "novelty", "quantity", "variety" and "quality" of the generated ideas [73, 74].

Therefore, from this short survey emerges that "novelty" is a key parameter in creativity studies, which deserves particular attention. Indeed, besides the concepts mentioned above (i.e. newness, originality and surprise), another distinction can be made according the definition provided by Boden [8], i.e. between psychological novelty and historical novelty. While metrics based on idea infrequency [48, 99] can be used for the first type (also called "a-posteriori" novelty [74]), historical novelty of generated ideas can be assessed by referring to an existing product or set of products. The latter type of metrics are also acknowledged as "a-priori" novelty metrics [74].

SNM belongs to the a-posteriori family of novelty metrics, and is based on the identification of recurring "key-attributes" (or functions [74]) of the examined ideas, as well as on the identification of the solutions adopted to implement the key-attributes. Moreover, a normalized weight is assigned to each attribute, indicating the relative importance according to the evaluators' opinion. Then, novelty is assessed by scoring the ideas generated for each key attribute, and the scores are summed together by multiplying them for the related weights. More precisely, the novelty score S for each attribute is calculated by Equation 1:

$$S_{ij} = \frac{T_{ij} - C_{ij}}{T_{ij}} \times 10 \tag{1}$$

where T_{ij} is the total number of solutions (or ideas) conceived for the key attribute i, and design stage j; C_{ij} is the count of the current solution for the attribute i, and design stage j.

Then, the overall novelty of each idea is calculated through Equation 2:

$$M_{SNM} = \sum_{i=1}^{m} f_i \sum_{j=1}^{n} S_{ij} p_j \tag{2}$$

where f_i is the weight of the attribute i, m is the number of attributes, n is the number of design stages and p_j is the weight assigned to the design stage j.

Unfortunately, even if no particular problem or difficulty is mentioned in the novelty assessment example reported by Shah, Vargas-Hernandez and Smith [74], some limitations and flaws have been highlighted in the literature. For example, it has been pointed out that uniqueness-based metrics could penalize experiments with large samples, where the probability of an idea to be assessed as novel decreases with the number of participants [77]. Furthermore, according to what stated above in this section, SNM (like any other a-posteriori novelty metric (e.g. [48, 54]), cannot be used to compare ideas with the outcomes of past idea generation sessions or with marketed products [81]. Therefore, SNM novelty score is dependent on the number of similar ideas conceived in a given set. Indeed the greater is the number of similar ideas, the lower is the overall novelty score (see Equation

1). Additionally, Brown [10] also highlighted the subjectivity affecting the identification of the key attributes, the subjectivity in identifying weights for each key attribute, and the need to define a clear separation of the items to be assessed between conceptual and embodiment design stages, in terms of design representations.
Perhaps, trying to overcome the flaws acknowledged for SNM, some improvements and or metric variants have been proposed in literature, which are still based on the same rationale (i.e. infrequency and idea decomposition). The aim of this work is to perform a systematic literature review to identify these contributions, to discuss about them, and to understand whether the acknowledged SNM flaws have been resolved or not.

3 Research method

Literature reviews should be based on a systematic and reproducible method for identifying, evaluating, and interpreting the existing body of knowledge about the investigated topic. Moreover, searches performed on the Web can be very efficient if specific questions, keywords and descriptors are conveniently and properly used with Boolean logic [26]. Accordingly, systematic literature reviews are often used in research, almost for every application and/or scientific field (e.g. [6, 7, 9, 38, 65, 82]), and also the literature review performed in this work has been planned, developed and performed by following a systematic and reproducible procedure. More in particular, the most impacting key points of systematic literature reviews [58] have been considered in order to develop the procedure represented in Figure 1.

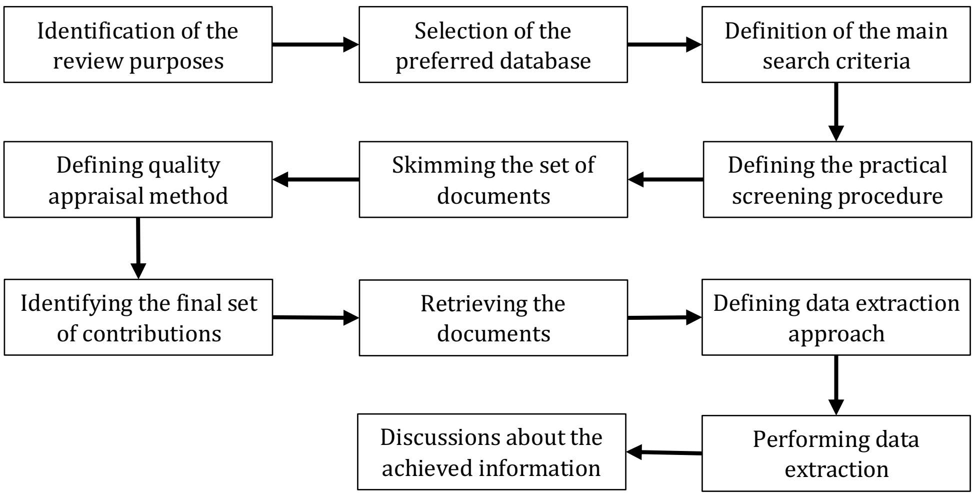

Figure 1. Systematic procedure adopted in this literature review.

First of all, the purpose of the literature review as it has been introduced in Section 1, was planned according to some issues faced when applying the metrics available in literature. Indeed, notwithstanding the presence of SNM variants, it was unclear how to select them and/or which of them can be considered sufficiently reliable. The Scopus database has been deemed very comprehensive by the authors of this work, because all of the most impacting conference proceedings and journals dealing with creativity are indexed in it. Therefore, the main search

strategy was based on the identification of those contributions directly citing the work of Shah, Vargas-Hernandez and Smith [74] (610 at October 2019). It was a quite easy operation performed by means of the Scopus search engine.
The screening process has been performed in practice by considering a suitable set of keywords available in Scopus ("Novelty" OR "Evaluation" OR "Design Evaluation" OR "Metrics" OR "Assessment" OR "Design outcomes" OR "concept evaluation" OR "Experiment" in the "exactkeyword" field of the Scopus search engine), leading to a subset of 87 articles. In particular, the authors of this paper have selected this set of keywords, because deemed as the most correlated with the aim of the work, i.e. to investigate about a specific family of novelty metrics (e.g. keywords like "creativity" or "innovation" were too general, because including a lot of works falling out of the scope of this work). Then, a further skimming process has been performed by reading the abstracts and the contents of the 87 papers, by identifying the contributions that comply with all of the following key points:

- There is an explicit reference to SNM.
- There is an explicit intention to overcome one or more SNM flaws.
- The ideas generated during the experiment constitute the reference for the assessment.
- Attributes and functions are identified a-posteriori by one or more evaluators.

After this further screening, the final set of contributions has been identified and the related documents retrieved, allowing to perform a comprehensive analysis.
Indeed, data extraction has been performed by considering the underpinning formulations of each proposal, together with the considered definitions of the main parameters involved in its application. Additionally, some boundary cases have been used to highlight possible issues affecting the proposed SNM variants.

4 Results from the literature review

As explained in the previous section, the resulting subset of 87 contributions has been analysed to find those explicitly aimed at overcoming one or more SNM flaws, but still preserving the SNM fundamentals. Therefore, many contributions were discarded because focusing on novelty metrics not strictly related to the SNM rationale (e.g. [44–46, 52, 54, 63, 80, 84, 95]), or even not strictly focused on novelty in general (e.g. [33, 43, 71, 90, 101, 103]). Moreover, many of the considered contributions only refer to applications of SNM for experimental purposes, without providing any substantial improvement (e.g. [5, 20, 24, 31, 39, 72, 86]).
Therefore, only eight contributions were identified to be compliant with the quality appraisal procedure, and among them, a particular group was characterized by the adoption of a predefined abstraction framework to identify the assessment parameters, i.e. the Genealogy Tree (GT). GT swivels on a hierarchical representation of ideas based on four items, i.e. physical principles (PP), working principles (WP), embodiments (EMB) and details (DET) characterizing each implemented function [61]. According to the graph shown in **Erreur ! Source du renvoi introuvable.**, representing an example of a GT, each node shows the number of ideas adopting a specific item variant while the lines hierarchically connect nodes belonging to the different items. Moreover, each level is characterized by a predefined weight, representing the different impacts that the four items are supposed to have on the Variety score.

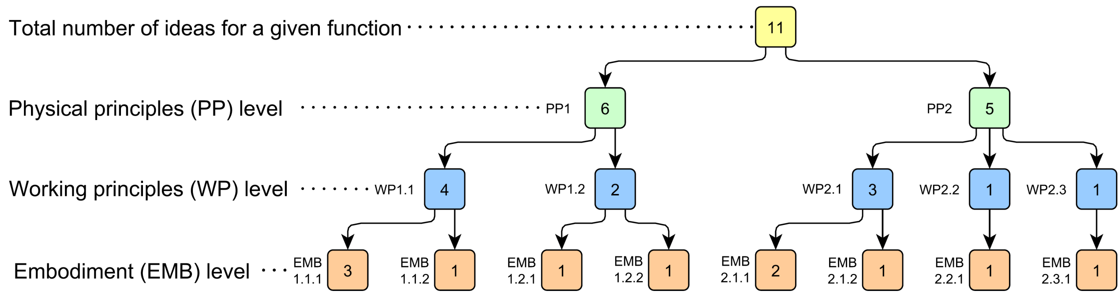

Figure 2. Example of genealogy tree [74]. The "Detail" level has been removed here since not considered by the reviewed metrics.

Hereinafter, the SNM variants exploiting the GT are called “GT-based”, while those that still refer to more general key attributes are called “attribute-based”. According to this distinction, Table 1 resumes the main characteristics and the advantages claimed for the reviewed contributions. A more detailed description of them is reported in the following subsections.

Table 1. Summary of the reviewed SNM variants

Type	Authors	Main characteristics	Claimed advantages
Attribute-based	Sluis-Thiescheffer et al. [78]	Novelty threshold based on the frequency of solutions	Improved reliability when in presence of missing attributes
	Fiorineschi, Frillici, and Rotini [28]	Novelty scores calculated on the attributes actually composing the concept	Improved reliability when in presence of missing attributes
GT- Based	Vargas-Hernandez, Okudan and Schmidt [87–89]	The attention is focused on the WP level	Improved accuracy and usability in boundary cases
	Peeters et al. [62]	The novelty score depends on the considered abstraction level	More information about the abstraction levels at which the treatment operates
	Fiorineschi, Frillici, and Rotini [28]	Novelty scores calculated on the functions and levels actually considered in each concept	Improved reliability when in presence of missing functions and/or levels
	Johnson et al. [49]	An additional abstraction level is added between functions and PP	Improved sensitivity with large sets of ideas and changes at higher abstraction levels

4.1 Attribute-based SNM variants

Sluis-Thiescheffer et al. [78] pointed out that when in presence of a large set of ideas, SNM can lead to high scores, even if similar solutions appear quite often. Accordingly, they proposed to assess novelty with a binary metric (novel or not novel), where an arbitrary "expectedness" threshold is used to identify less frequent (novel) ideas.
The threshold selected by the cited authors is the 75th percentile for the frequencies of ideas generated for each attribute (i.e. the 25% of ideas having lower concurrencies are novel). Therefore, their metric can be represented as it follows (Equation 3):

$$M_{ST} = \begin{cases} 1 \ for \ C_i \leq P \\ 0 \ for \ C_i > P \end{cases} \quad (3)$$

where C_i is the number of occurrences of the idea for the attribute i, and P is the percentile which can be chosen between the 0.5 and 1.

More recently, it has been highlighted the impossibility to perform correct assessments of ideas when some attributes are not implemented, and a proposal to deal with that problem has been proposed accordingly [28]. In particular, for a single design stage (the conceptual one) the proposal suggests to calculate a modified M'_{SNM} as shown in Equation 4:

$$M'_{SNM} = M_{SNM} \frac{1}{\sum_{i=1}^{p} f_i} \quad (4)$$

where p is the number of attributes actually involved in the assessed idea, while the other terms are the same used in Equation 2. Since the numerator is the sum of the normalized weights of all attributes (i.e. 1), M'_{SNM} becomes equal to M_{SNM} for ideas implementing all the attributes (i.e. when also the denominator is equal to 1).

4.2 GT-based SNM variants

Vargas-Hernandez, Okudan and Schmidt (2012) pointed out that some improvements could be done in terms of capability of SNM to accurately reflect changes on the set of ideas, and to deal with boundary cases. Accordingly, they proposed two variants. The first variant proposed in Vargas-Hernandez, Okudan and Schmidt (2012) (also used in Vargas-Hernandez, Schmidt and Okudan (2013)), focuses the attention on the WP level, and suggests a new formula for calculating novelty, as shown in Equation 5:

$$M_{VOS} = \frac{1}{C_{wp} m} \quad (5)$$

Where C_{wp} is the count of occurrences in specific WP branches (i.e. the number of nodes at the Embodiment level, which are under the same WP node), and m is the number of nodes at the WP level. The same authors (in the same conference) presented also a very similar variant [88], where a slightly different equation is suggested (Equation 6):

$$M_{VSO} = \frac{N}{C_{wp} m} = M_{VOS} \times N \quad (6)$$

Where N is the total number of ideas in GT (i.e. the count of all ideas at the Embodiment level), while C_{wp} and m keep the same meaning. Note that in both cases, instead of "Embodiment" level, the authors use the term "ideas".
Differently, the metric of Peeters et al. (2010) is substantially based on the concept that an idea can reach higher novelty scores when the difference can be observed at higher abstraction levels. Accordingly, they use GT items in place of the SNM attributes, with the set of weights proposed by Nelson et al. (2009), but continue to apply very similar versions of Equations 1 and 2 (Equation 7).

$$M_P = \sum_{i=1}^{m} f_i \sum_{j=1}^{o} S_{ij} w_{ij} \tag{7}$$

where f_i is the normalized weight of function i, m is the number of functions, o is the number of items (PP, WP and EMB), and w_{ij} is the normalized weight assigned to the item j, related to the function i. In particular, Equation 8 is calculated as it follows (for a single design stage):

$$S_{ij} = \frac{T_i - C_{ij}}{T_i} \times 10 \tag{8}$$

T_i is the total number of ideas for the function i, c_{ij} is the number of the current ideas for the item j under the function i. Therefore, besides the use of functions and items in place of more general key attributes, this proposal preserves the same logic of SNM. Accordingly, it presents similar drawbacks in presence of ideas where only a part of the required functions and items is represented/implemented. Nevertheless, an enhanced version of M_P has been proposed [28] to deal with missing functions and/or items (Equation 9):

$$M'_P = M_P \frac{1}{\sum_{i=1}^{q} f_i \sum_{j=1}^{r} w_{ij}} \tag{9}$$

where f_i is the normalized weight of function i, m is the number of functions, o is the number of items (PP, WP and EMB), and w_{ij} is the normalized weight assigned to the item j, related to the function i. Moreover, q is the number of functions actually involved, r is the number of items actually involved for a given function i. Similarly to what explained for Equation 4, in presence of a set of ideas implementing all functions and representing all items, M'_P and M_P lead to the same novelty scores.
Johnson et al. (2016) proposed a new metric variant based on GT, with the additional "Strategy" level, intended to furtherly group solutions at an intermediate abstraction level between function and PP. In particular, they suggest a new way of calculating the novelty (M_J) for a single function, as reported in Equation 10:

$$M_J = \sum_{j=1}^{m} \frac{(1-P_j)s_j}{2} \tag{10}$$

where P_j is the count of responses at the j level divided by the count of responses of its parent, i.e. the count of solutions in the node at the higher abstraction level, and s_j is the weight assigned to the level j.

5 Considerations about the reviewed contributions

In this section, the reviewed variants are analysed in detail, in order to understand whether the issues highlighted for the original version of SNM have been comprehensively resolved. Unfortunately, it is possible to anticipate that the reviewed SNM variants present some non-negligible flaws, as resumed by Table 2.

Table 2. Summary of the flaws observed for the SNM variants

Metrics	Identified flaws
Sluis-Thiescheffer et al. [78]	The binary assessment (novel or not novel) is affected by the subjective selection of the novelty threshold. The considered case study is characterized by incomplete ideas, but the proposed metric does not face the problem of missing attributes.
Fiorineschi et al. [28]	Impossibility to reach the expected maximum novelty value in specific boundary cases.
Vargas-Hernandez, Okudan and Schmidt [88, 89]	Inconsistent reference to SNM; mathematical non-sense when missing EMB-related information; impossibility to assess ideas missing WP-related information; siblings at EMB level get the same score; the sum of novelty scores in the GT is always 1.
Johnson et al. [49]	Non-conventional definition of PP-WP-EMB. Inconsistent results with boundary cases.

The following paragraphs report a detailed description of the flaws and/or limitations and/or criticalities observed for the reviewed SNM variants.

5.1 Sluis-Thiescheffer et al.

Sluis-Thiescheffer et al. (2016), in their experiment observed that an idea that appears 160 times on a set of 816 ideas still gets a score higher than that of an idea appearing only four times (on a set of 13 ideas). Considering the presence of 62 participants, they argued that in the first case, an idea generated 2-3 times for each participant is getting a quite higher score than an idea generated 1 time every 16 participants.

Analysing their discussion, however, it is possible to observe that they were examining two different attributes in the same design task. While one attribute is used very frequently (816 times), the other one is rarely used (only 13 times). Unfortunately, SNM doesn't take into account the uncommonness of attributes, since all attributes are expected to be implemented in the original version of Shah, Vargas-Hernandez and Smith (2003). In other words, Sluis-Thiescheffer et al. (2016) somehow highlighted that for certain experiments, it is useful to take into account the different occurrences of attributes (and not only of the related ideas). However, to solve this problem, it is first necessary to correctly deal with the different number of attributes composing the ideas, and secondly, it is necessary to consider the uncommonness of attributes in the final score. Concerning the uncommonness of attributes, Sluis-Thiescheffer et al. (2016) didn't provide any hint.

The same authors also claimed the possibility of their proposal to deal with concepts implementing only a part of the total set of key attributes, but failed in comprehensively explain how it solves the problem. More precisely, for each idea, they suggest to calculate the sum of the novelties calculated for each attribute, in order to obtain the overall novelty. Nevertheless, if an idea is composed only by part of the total attributes, the minor number of scores that are going to be summed together negatively affects its overall score. This is in contrast to what recently observed for SNM, i.e. that missing attributes should affect quality score, but not novelty [28].

A further criticality that can be observed in the work of Sluis-Thiescheffer et al. (2016), is that the same authors also argued that SNM could get high scores even if ideas appear frequently, and this is the main reason why they formulated their proposal (Equation 5). However, a boundary case example can be used to demonstrate that the proposed metric does not sufficiently overcome the problem. For instance, a set of 10 ideas for a single attribute, where only three different types of ideas are generated, and one of these ideas appears eight times while the other two only one time each (see Figure 3) .

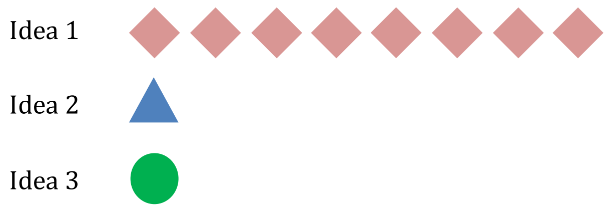

Figure 3. Boundary case considered to highlight the criticality of the threshold assignment.

In such a case, we easily observe that by considering the suggested 75th percentile, according to Equation 5 all the ideas are assessed as equally novel because get the same score of 1. It means that although the selection of the percentile is arbitrary, when in presence of many attributes it can be difficult to avoid unbalanced assessments among them (e.g. a certain percentile can fit well for certain attributes while not for others).

5.2 Fiorineschi et al.

In order to understand why M'_{SNM} is not a comprehensive solution to the problem, Table 3 shows an illustrative and generic set where five different types of ideas (C1, C2, C3, C4, C5) constitute the reference universe of solutions (for a single design stage). In particular, only C1 implements all the three attributes (A1, A2, A3), while the others miss one or two of them.

Table 3. Generic set of ideas with "missing attributes". Different ideas for each attribute (A1, A2, A3) are coded with a different symbol.

Idea	Occurrences	A1 solutions	A2 solutions	A3 solutions
C1	1	α	X	Δ
C2	93	β	Y	-
C3	2	γ	-	-
C4	2	γ	Y	-
C5	2	γ	Z	-

By applying Equations 1, 2 and 3 on this set under the hypothesis that the three attributes share the same normalized weight of 0.33, the novelty scores listed in Table 4 show how the presence of missing attributes can affect SNM, and how M'_{SNM} is not sufficient to solve the problem.
In particular, since C1 is composed by unique solutions for each attribute, it should get the highest score (i.e. near to ten). Indeed, the solutions implementing each attribute appear just one time in the set of 100 ideas. However, according to Equation 1, T_{ij} is the total number of ideas for "the key attribute i". It means that for attribute A3, in this case T_{ij}= C_{ij}=1, thus leading to a completely erroneous S value of zero for the solution "Δ" (i.e. the unique solution present for the attribute A3,

appearing only one time in the whole set). This is why both M_{SNM} and M'_{SNM} cannot reach the required values.

Table 4. Individual novelty scores calculated by applying SNM and SNM' on the generic set of Table 3.

Idea	M_{SNM}	M'_{SNM}
C1	6.53	6.53
C2	0.33	0.51
C3	3.10	9.40
C4	3.20	4.86
C5	6.34	9.6

Besides the particular problem derived from the boundary conditions represented by C1, Table 4 also shows that the differences between M_{SNM} and M'_{SNM} can be quite high in other circumstances. However, the actual reliability of certain M'_{SNM} values is doubtful. For example, ideas C3, C4 and C5 share the same solution (γ) for the attribute A1 and appear the same number of times (two each). These ideas all miss the attribute A3 but differ in the implementation of the attribute A2. In particular, C3 misses such attribute while C4 implements it with the solution "Y" and C5 with the solution "Z". According to Equation 3, the novelty score of C3 jumps from a quite low 3.10 (obtained with the original SNM) to a very high 9.40, only because is missing two attributes. Differently, the other two ideas get scores which take into consideration the uncommonness of the solutions implemented for attribute A2 (very frequent for Y, and very rare for Z), but are still affected by the absence of solutions for attribute A3. In other words, Equation 3 privileges the partial S scores of implemented attributes, but does not consider the actual uncommonness of the overall solution. An additional boundary example can be used to better understand the latter problem. Considering the two different types of ideas A and B in Figure 4, they can be reasonably decomposed with two attributes or functions: "ink deposition" and "making light".

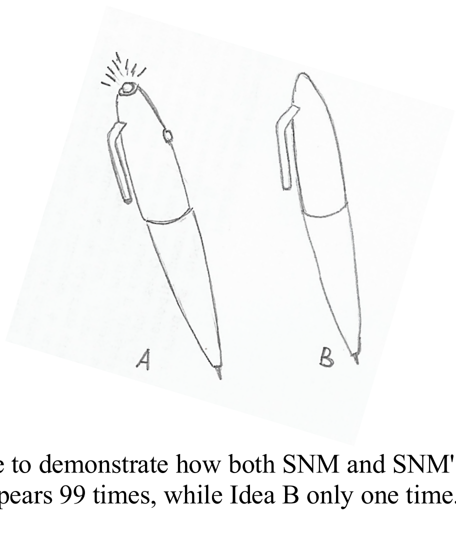

Figure 4. Additional example to demonstrate how both SNM and SNM' cannot correctly deal with missing attributes. Idea A appears 99 times, while Idea B only one time.

Idea A implements both the attributes (a pen with a light) while the idea B missed that of "making light". Considering a boundary case where the idea A appears 99 times and B only one time, the novelty scores according to both M_{SNM} and M'_{SNM} are equal to zero for both the assessed ideas. However, although Idea B uses the same solution for the first attribute (used 100 times on a set of 100, and thus leading Equation 1 to zero), it is the sole that does not present any solution about how to dispense the water. Perhaps, this could be a problem affecting the "quality" of the conceived idea, but according to the set of metrics proposed by Shah et al., this parameter should be assessed independently from novelty. Strictly in terms of novelty, Idea B, in relation to Idea A, is highly infrequent and cannot get the same novelty score of zero. Consequently, Equation 3 does not comprehensively solve the problems of SNM.

5.3 Vargas-Hernandez et al.

The first problem that we observed in the work of Vargas-Hernandez, Okudan and Schmidt [87, 89], is that they consider Equation 11 as "the original version" of the metric, where T is the total number of ideas, and C_{wp} is the number of occurrences in a WP branch:

$$S_{ij} = \frac{\mathrm{T} - C_{wp}}{C_{wp}} \times 10 \tag{11}$$

However, the recalled formula is inconsistent if compared with Equation 1. Therefore, also the flaws mentioned by the authors are inconsistent as well, because they seem to refer to Equation 11 instead of Equation 1.

Nevertheless, the main issues concerning M_{VOS} (Equation 3) are described here in the following:

- Ideas with missing items at the WP level cannot be assessed, because the metric does not consider upper levels.
- If a certain idea is expressed only in terms of WP, then missing the EMB description, $C_{wp} = 0$, Equation 3 leads to a mathematical non-sense (1 divided by 0).
- Siblings at the EMB level get the same score [49].
- The sum of novelties of ideas in GT is always 1, thus the mean novelty is strictly dependent on the number of ideas.

(The same issues observed for Equation 3 are valid also for Equation 4).

Concerning the last point, it is important to observe that Equation 3 has been used by the same authors to assess the mean novelty score in a specific experiment [89], but it was not possible to verify the results here. According to the available information, they calculated the average novelty for each idea, then calculated the average novelty for each student, and then the average novelty for each group. Unfortunately, they didn't provide sufficient data to repeat the calculations. Moreover, in another work they used Equation 4 instead of Equation 3 on the same set of data, obtaining exactly the same results in terms of means and standard deviations [88].

5.4 Johnson et al.

Johnson et al. [49] based their work on some criticalities that they observed for SNM and M_{VOS}. However, several doubts arise when reading the motivations behind the proposed metric. First of all, the authors used SNM by reducing it to the simple application of Equation 1, because their case study was constituted by only one function. Other a-posteriori versions based on ideas infrequency can be found in literature, which can be used when a more detailed decomposition of ideas is not needed or possible [48, 52]. It is not clear why they referred to SNM. Moreover, they assert that

SNM has been originally developed to be applied on sketches, but without providing any supporting reference. Actually, Shah, Vargas-Hernandez and Smith [74] applied SNM on a case study where ideas were represented by physical prototypes. Similarly, the authors also assert that SNM can be successfully applied only on ideas developed at the embodiment level. However, SNM is based on a very broad and general definition of "key attributes", which can potentially be applied at any abstraction level. The authors also observed that M_{VOS} leads to inconsistent results in boundary cases. More precisely they refer to the case where an ideas appears only one time in GT, i.e. a unique EMB below a specific WP with no other ideas. According to the authors, in this case M_{VOS} leads to the highest score, but it is not correct. Indeed, it seems that they wrongly consider m as the number of EMB below a certain WP. On the contrary, according toVargas-Hernandez, Okudan and Schmidt [87], in this case the novelty score depends only on the number of different WPs (m), since C_{wp} is 1. An idea could get the score of 1 in M_{VOS} only in the extreme case where no other ideas are generated in the same experiment. Another criticality concerns the new additional level called "strategy". The actual need of this additional abstraction level is doubtful. Indeed, authors seem to use a non-conventional definition of PP-WP-EMB (e.g. they considered "Optimization" as a physical principle), and this can be the reason that led them to add a further (but non-comprehensively defined) level.

In addition, it has been found that the proposed metric has a problem for boundary cases, which leads to inconsistent results [30].

6 Discussion

Although other contributions deal with SNM variants [29, 30], the literature review described in this paper is based on a more comprehensive search strategy, and it highlights original and fundamental issues. More specifically, Fiorineschi et al. [28] pointed out that the solution proposed by Sluis-Thiescheffer et al. [78] suffers of some additional problems. Furthermore, this paper highlights that some problems also affect the solution suggested by Fiorineschi et al. as well. Another contribution from the same group of authors deeply discusses the issues affecting the acknowledged SNM-variants, and proposes a possible selection framework to support scholars in orienting through the different metrics [30]. However, the issues highlighted in Subsection 5.2 of this paper put more emphasis on the actual need of a thorough understanding of pros and cons of the available metrics. Although the framework proposed in [30] could provide a first aid to the scholars, it is still not possible to extract comprehensive guidelines for supporting metric selection.

Nevertheless, the open research questions mentioned in [30] are still valid and important:

- can other abstraction frameworks be used for GT-based metrics?
- Which is the right set of weights for the abstraction levels?

The same authors also proposed a possible solution to calculate the weights to be assigned to the SNM attributes but the proposal has not been tested yet and thus it cannot be considered for experimental purposes.

Other contributions are available in literature, which mention the SNM-variants described in this paper (e.g. [29, 40–42, 49, 97]), but often they neglect in-depth analysis of the metrics or focus only on few of them. For instance, Weaver et al. [97] focused their attention to three specific metrics, among which SMN and the variant proposed in [49]. They concluded that SMN should be preferred when dealing with rarity of ideas.

Therefore, according to the limits of the work described in this paper (see Section 9), it is possible to assert that, at the best of the authors' knowledge, this is the most detailed and up-to-date literature review about SNM-based novelty metrics.

7 Achieved results

The contributions identified and reviewed in this paper constitute the current state of the art of the available SNM variants, which are claimed to enhance the original metric and/or to fill the existing gaps. Unfortunately, the analysis performed in this work show that some non-negligible flaws are still present. Indeed, while the subjectivity issues highlighted by Brown [10] have not been faced at all, some of the proposals even introduce other criticalities that need to be carefully considered when selecting the assessment approach. In Section 4.2 the mentioned issues have been comprehensively introduced, thus allowing researchers and scholars to retrieve fundamental information about the suitability of the metrics according to their experimental requirements.

Concerning the hypothesis made in Section 1, because of the observed flaws characterizing the reviewed metrics, it is possible to assert that it cannot be confirmed, i.e. the problems affecting SNM have not been resolved in a comprehensive manner.

Nevertheless, depending on the experimental and research requirements, some of the reviewed approaches could provide support for performing systematic idea decomposition during the novelty assessment (e.g. the GT-based ones), but it is extremely important to be aware of the flaws or doubts currently affecting the considered metric. Especially concerning the problem around the “missing attributes”, the question is still open, because the currently available proposals [28] provide a first rough solution, which still needs to be optimized in detail in order to correctly work with any possible case study.

8 Conclusions

The paper reviews a set of metrics for the novelty assessment according to the analysis of the information retrieved from the literature. More in particular, the objective of the investigation was to verify whether the current variants are capable to overcome some specific flaws acknowledged to the original SNM metric. The results of the investigation show that the reviewed contributions not only fail to provide a comprehensive solutions to the original SNM flaws but in addition they also introduce other drawbacks that could results potentially dangerous for scholars who need to use novelty metrics for assessment tasks (see section 4.2 and Table 2). Indeed, the analysis of the considered SNM variants shows that the degree of subjectivity and the difficulties to deal with ideas having “missing” attributes are still open issues also for the SNM variants. The paper stresses the importance for the users to evaluate carefully the needs of the experimental activity and to select the most appropriate novelty metric, in order to avoid misleading results. Accordingly, some warnings have been provided to the scholars interested in using the SNM variants to assess the novelty of ideas.

9 Limits, research hints and expected impact

The main limitation of this work is intrinsically related to its nature of being a literature review, thus neglecting to perform more comprehensive analysis and investigations about the considered metrics. However, it paves the way for future research activities, which if performed should contribute to better understand the actual application field, limits and potentialities of novelty metrics based on idea infrequency and decomposition.

Accordingly, there are several other arguments about this kind of novelty assessment approaches, which need to be investigated in depth. For example, when in presence of sequential design sessions, the reference universes of ideas should be selected with care, in order to correctly evaluate the effects of the investigated treatments [29]. Moreover, it also emerges the absence of comprehensive studies about the subjectivity of the metrics. This is a critical gap to be filled, because especially when the idea decomposition is performed without any reference framework, the selection of the attributes and/or functions and the related weights can be heavily affected by subjectivity. Accordingly, the concept of function is far to be standardized [22, 92, 93] and can sensibly affect the idea decomposition [23]. Therefore, the investigation around different ways to decompose concepts or ideas to be assessed with novelty metrics is a critical activity that deserves to be investigated in depth. This issue obviously affects also the reviewed GT-based metric, where it would be also interesting to test different abstraction frameworks for the definition of the GT levels. Indeed, the Function-Behaviour-Structure [34, 35] and the SAPPHIRE framework [68, 79] could provide additional hints, as well as the Subject-Action-Object (S-A-O) framework [11, 17, 32].

The academic nature of this work implies that the main impact is expected for scholar and researchers involved in experimental activities about idea generation and design. More specifically, thanks to the flaws and gaps highlighted in this paper, it is expected an improved awareness about the criticalities affecting the available SNM-based metrics, especially in terms of their underpinning rationale and/or definitions. Moreover, as highlighted in the precedent subsection, it is also important to carefully consider the actual concepts of functions and/or attributes, as well as the followed rationale behind the idea decomposition process. Therefore, an important suggestion that can be extracted from this work is the following one: when interpreting and/or discussing experimental results available in literature, it is important to carefully verify the availability of comprehensive information about the assessment rationale. Indeed, as shown in this paper (limited to the a-posteriori SNM-based approaches), different rationales, definitions and/or decomposition procedures can be affected by different issues.

Concerning industry, it is very difficult to extract or to imagine a concrete impact. However, this problem is not limited to this work, but to a-posteriori metrics in general. Indeed, while it is possible to suppose that industry is mainly interested to innovation (and then to the historical novelty), possible uses of a-posteriori metrics for psychological creativity investigations need to be discussed. This is a further gap which needs to be filled in literature, because a-posteriori novelty assessment approaches could be conveniently used in industry (for example) for verifying the presence of design fixation among individuals and/or departments and/or design staffs. This could support the industry management to highlight most creative subjects or departments, and consequently to better plan the assignment of particular design tasks, as well as to plan creativity-related courses to improve the less creative subjects.

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