Encoding the citations life-cycle: The operationalization of a literature-aging conceptual model

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Abstract: In this study, we introduce a new literature-aging conceptual model (Bailón-Moreno, 2005) to study citation curve and to discuss its implications. First, we improve the conceptual model by adding a period to describe the "death" of citations. Second, we offer a feasible operationalization for this conceptual model and implement a set of cross-discipline publications in the Web of Science to test its performance. Furthermore, we propose two measurements according to the new model—SP and RP—to capture the patterns of citation curve of publications. For example, we find that half papers in Arts & Humanities published in 1985 almost receive no or extremely few citations in the first five years after their publication; on average, those papers in Arts & Humanities have a five-years-long period when their citations grow rapidly. In addition, we observe a special phenomenon named "literature revival" as some publications may have multiple citation life cycles, which received little attention from current researches. Finally, we discuss the implications of our study, especially the application of the SP and RP in improving scientific evaluation and collection development in library, and the inspiration of "literature revival".

Keywords: Scientometrics, Literature obsolescence, Research evaluation, Bibliometrics

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INTRODUCTION

How many years do you have to wait until your papers can be acknowledged and cited by the scientific community? The answer is not obvious at all. Individual papers attract citations depending upon the importance and usefulness of the results presented. However, the road to be cited or not cited varies in difficulty because publications have distinct levels of acknowledgement within the scientific community—from those implicitly or explicitly "highly cited", to those "never cited" (Garfield, 1973). The citation based-system is affected by the flood of mediocre papers, self-citation cartels, and lengthy reference lists, among other factors (Fire and Guestrin, 2019). Additionally, publications also have distinct levels of durability (Costas, Van Leeuwen & Van Raan, 2010) and aging (Glänzel & Schoepflin, 1995; Sengupta, 1992), and their citations are influenced by multiple reasons/factors (Bornmann et al., 2012; Cole, 2000; Liskiewicz et al., 2021; Moed, 2005).

Among these, aging of publications or literature obsolescence refers to the phenomenon that the content/value of literatures is increasingly out of date and is utilized less as time goes by (Gupta, 1990). Since the pioneer work of Gross and Gross (1927), indicators and mathematical models have been proposed to study aging publications; see, for example, the length of half-life (Tsay, 1998), the Price index (Egghe, 2010), regression models (Abramo, D'Angelo & Felici, 2019), and correlation analyses (Wang, 2013) among others. These studies have painted a macro-level picture of the publication aging issue and have shed light on science policy decision-making in research evaluation (Clermont, Krolak & Tunger, 2021; Costas, Van Leeuwen & Van Raan, 2010); the reputation and impact of researchers in academic careers (Liskiewicz et al., 2021; Petersen et al., 2014), and library information resource services (Fosmire, 2004; Kinney, 2007; Perrault et al., 1999; Sangam, 1999).

As an important contribution to studying individual publications' obsolescence, Bailón-Moreno et al. (2005) proposed a Generalized Model of Ageing-Viability (GMAV model) that conceptually partitioned the period after a paper was published into four periods according to its citation rate—Periods X, P, C, and N; in our study, we also call them Periods I, II, III, and IV. Nonetheless, Bailón-Moreno and colleagues' work remains at a conceptualization level without presenting detailed operationalization, which hinders future researchers from widely adopting their model in practice. To this end, the current paper offers a feasible operationalization of Bailón-Moreno et al.'s (2005) GMAV model. The operationalization is based on the temporal-based annual citation counts of a given publication. We showcase the usage of our operationalization by particularly focusing on the lengths of Period I (sleeping period,

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abbreviated as SP) and Periods II+III+IV (recognition period, abbreviated as RP).

Yet, to quantify the length of Periods I-IV, we also need to empirically define Period V (a period after Period IV), in which publications do not receive citations (no longer being "adopted"). This is necessary when people calculate the length of RP (or Periods II+III+IV). In this paper, our operationalization also highlights this new contribution.

Besides, most aging studies have been applied at the country level (see for example Abramo, D'Angelo & Felici, 2019; Clermont, Krolak & Tunger, 2021), or restricted to scientific disciplines or specialties (see for example McCain & Turner, 1989; Rovira-Esteva, Aixelá & Olalla-Soler, 2019) with different time windows (see for example Glänzel, 2003; Wang et al., 2013). However, long citation periods bring the benefit of compensating for short, random fluctuations to a certain degree by lengthening the citation period. In this empirical study, we adopt all publications in 1970-1985 from the Web of Science database covering papers in all disciplines. Our dataset covers at least a 30-year-long time window after they were published to guarantee that the citation window is of sufficient length empirically. We believe that investigating individual paper-level obsolescence using a long period of time helps understand the laws in the citation dynamics more deeply and will guide practices in a broad spectrum of topics related to the science ecosystem/environment, such as their effects in building citation indicators, evaluating scientific careers, or developing a library collection.

The rest of this paper is organized as follows. We first present previous related studies on literature obsolescence. We then detail how we operationalize the model. Next, we introduce our dataset and show the empirical results about the two focused stages, SP and RP, both static and temporal perspectives, and a special phenomenon which tends to be neglected by many previous studies and which we call "literature revival". Finally, we discuss potential implications and suggest future work.

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LITERATURE REVIEW

To the extent that citation analysis is used as a continuing measure of certain types of scientific activity, aging of scientific publications or literature obsolescence[1] is still of interest for the study of scientific communication (Pollmann, 2000). Literature obsolescence has been widely studied in scientometrics and bibliometrics (Glänzel & Schoepflin, 1995; Sengupta, 1992). Xu and Xu (2006) pointed out that literature obsolescence research has significance in improving information management, raising the efficiency of information services, and revealing the law of development of science and technology (Metz, 2011; Wang et al., 2019). Obsolescence studies help the working librarians and information officers in a great deal of decision-making. For example, Chen (1972) conducted usage studies, analyzing the age of references cited in source papers of psychology at different phases of its development, Nicholas et al. (2005) adopted the usage data of readers to explore the differences of obsolescence rate among subject fields and content types, and Sangam (1999) concluded that aging analysis would assist a library to derive, review, and incorporate data on obsolescence in the field of psychology, serving as an example in describing how to go about bringing the librarian and the researcher together.

On the one hand, far from the common belief that citations of a publication are an indicator of quality, the reasons and factors behind citations are diverse. For example, Radicchi et al. (2008) argued that citations received by publications strongly depend on their disciplines and that, while measuring with a relative indicator, those publications showed a universal pattern regardless of their disciplines. Factors such as publication language, topic or approach can exert a notable influence in citations (Moed, 2005). Reputation and esteem are also factors influencing the chances of being cited (Liskiewicz et al., 2021). For example, the "Matthew effect" is the tendency to cite

[1] We use aging of scientific publications and literature obsolescence indistinctly to refer to the same concept.

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articles written by well-known authors rather than drawing attention to the work of lesser-known researchers, even if the latter's work is similar or better in quality, which affects the reputation of these authors. This factor has important implications for academic promotion (Petersen el al., 2014) or acquisition of research funding (Bol et al., 2018).

On the other hand, there is no uniform consensus in the scientific literature about how long the period that a citation analysis is based on should be (Clermont et al., 2021). Burton and Kebler (1960) posit that classic literature has a long half-life, while ephemeral literature has a much shorter half-life with an exponential decay rate in the citation of physics literature (Gupta, 1990). Wainer et al. (2011) discovered that the mean age of references in computer science is 5 to 6 and the publications having high citations changed quickly with year. Gupta (1998) found that the age of references cited in source papers of the theoretical population genetics specialty at different phases of its development was the best modelled, according to lognormal distribution. Wang, Leng, and Li (2019) proposed a Laplace transfer-based model to calculate the parameter of obsolescence process of publications. Among the different equations of various models to analyze the time dependence of behavior of citations, power-law, exponential, and logistic functions have been commonly used (Egghe, Ravichandra Rao & Rousseau, 1995; Glänzel, 2004). Sangwal (2011) proposed a new approach analyzing the growth of citations $L(t)$ at time t as a function of the publication duration t using equations based on power law, exponential growth, and progressive nucleation mechanism (PNM). In the comparison of the three models, the latter describes the data reasonably better than the other two, and it gives information on the processes of citation sources and the growth of these citation sources. Modeling the growth behavior of cumulative citations according to the progressive nucleation mechanism reveals that the time dependence may be represented in two citations periods when analyzing researchers' publication careers (Sangwal, 2013).

Extant related work can be summarized as two different levels (macro and micro

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levels), differing from each other in terms of their research objects—the former focuses on a set of publications (e.g., those in a certain discipline) while the latter focuses on individual publications. Among the various models, on the macro level, Half-Life is an important indicator for measuring obsolescence. Yet, there are two ways of calculating half-life, namely diachronic and synchronic strategies. Generally, both strategies are equally feasible to measure literature obsolescence, but different results would be obtained with the two strategies when considering other factors such as the growth of literatures (Egghe, Rao & Rousseau, 1995). The diachronic strategy first selects a set of publications and collects their citations' data in the following several years (after their publication); as for the synchronic strategy, we select a particular year and examine all past publications cited by the publications in this particular year (Sangam, 1999). For example, the half-life proposed by Bernal (1958) is diachronic. Later, another concept of half-life based on the synchronic method was proposed by Burton and Kebler (1960), and is defined as the publication interval of the 50% recently published literature cited by a certain current publication (of a journal or a discipline), which is also called median citation age. For a more comprehensive review of this topic, we refer to Urbizagástegui-Alvarado (2014). Although divergent, both strategies have been widely used in the calculation of the degree of literature obsolescence. For example, the Journal Citation Report (JCR) adopts both concepts and offers two indicators for journals, namely cited and citing half-life: the former equals the interval of the 1/2 new citing papers of a journal while the latter is the interval of the 1/2 new references of this journal. As the value of the half-life indicator may vary in different years and disciplines, the average value among years is generally used to describe the degree of obsolescence.

In addition to the half-life indicator, people also adopt the Price Index to characterize obsolescence, calculated by dividing the number of references published in the previous five years by the total number of references published in the current year. Egghe (1997) proposed the N-year Price Index to supplement the original Price

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Index by extending the five-year-long time-window of this indicator to any integer, N. He pointed out that there exists a certain relationship between Price Index and half-life indicator. Additionally, on a more theoretical yet crucial level, some research has also been devoted to exploring the law of obsolescence and to constructing some literature obsolescence models (e.g., Avramescu, 1979; Burton & Kebler, 1960). Meanwhile, some scholars believed that the influencing factors of obsolescence are complex and it is difficult to consider all these factors (Petersen et al., 2014). Thus, classical models established under the premise of an unclear situation can only be regarded as the representation of the original system. Therefore, they proposed a posteriori model called the grey dynamic model (GM).

Compared with macro-level studies, the number of micro-level approaches is much smaller, but it offers more details on the process of publication aging. For example, Wei and Qian (2005) pointed out that every measurement of obsolescence was an estimation in statistics, and the half-life indicator or Price Index of literature could be regarded as point estimation while micro-level approaches could be seen as interval estimation. In other words, micro-perspective research could calculate the probability that the true value falls into this interval, which outperforms macro-level studies. On the other hand, Zhang and Glänzel (2017) found that the distribution of the Price Index of individual papers publishing in two journals with a similar Journal Price Index might be extremely different. For example, supposing there are two journals, one is composed of 50% small Price Index papers and 50% large Price Index papers, and the other is completely composed of papers with medium Price Index papers. This would result in a similar macroscopic Price Index (journal's Price Index), yet the microscopic Price Index (paper's Price Index) would be quite different, as aforementioned.

As a pioneer, Price (1963, 1976) first linked micro-level studies with the half-life indicator. He extended the concept of half-life, and proposed that the half-life value of an individual publication equals the interval of publication of its new 50% citing papers. Price (1963) indicated that the half-life of a paper was about 1.5 year, which meant that

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half literatures which cite this literature were published within 1.5 years after the publication of this literature. Guo, Huang, Jin, and He (2010) adopted this definition to calculate the half-life of each paper and applied it in the impact evaluation for interdisciplinary papers. Li (2020) proposed Character String Coding for Literature Ageing (CSCLA) based on the GMAV model (Bailón-Moreno et al., 2005) and explored the translations of the obsolescence states of publications.

RESEARCH OBJECTIVE

The **main objective** of our study is to encode the citation curves of publications with various patterns. Specifically, we have three sub-objectives. 1) Introduce and improve a new conceptual model for researches on literature-aging or citation curve from the perspective of individual publications; 2) Offer a feasible operationalization for the conceptual model and explore the patterns of citation curve of publications in various disciplines and temporal characteristics; and 3) Discuss how to utilize the literature-aging stages, especially the SP and RP proposed in this study, to improve scientific evaluation and collection development in library.

METHODS

Model

In his model, Bailón-Moreno (2005) proposed three transitions based upon the aforementioned four periods: the transitions from period P to C, from C to N, and from N to C. These transitions represent an increase or decrease of the literatures' citations in different aging stages. While Bailón-Moreno's model remains at the conceptualization level, we operationalize the model in a doable way (and adopt a numbered naming strategy for simplicity):

Period X (Period I): The publication's citation count conforms to a zero-growth model, and the number of citations is equal to or is approximately equal to zero;

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Period P (Period II): The publication's citation conforms to an exponential model, and its citation count has an accelerating growth;

Period C (Period III): The publication's citation conforms to a linear model, and its citation count grows at a smooth speed;

Period N (Period IV): The publication's citation conforms to the deceleration stage of a logistic model, and its citation count decreases over the years.

This operationalization indicates a temporal-based aging process of an individual paper by examining the temporal change of its annual number of citations. Generally, one paper will have a Period I after its publication, then its citations may grow quickly in Period II. Later, the growth rate decreases and its citations maintain a slow growth, i.e., Period III. It then comes to Period IV and decays. Finally, which is what we would like to highlight, the publication will not be cited and adopted anymore (Period V). Note that Period V was not mentioned in Bailón-Moreno et al.'s model. Yet, to operationalize Periods I to IV (especially their lengths), we have to define this period when there are no additional citations received. It is worth noting that some publications will not experience all these periods, e.g., "uncited papers" only have Period I[2]. The process is illustrated in Figure 1.

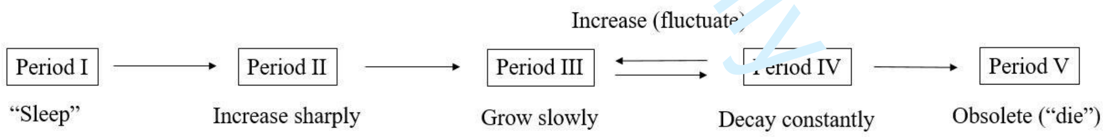

Figure 1. Annotation of the publication obsolescence process.

We then further stipulate the rules of operationalization as per van Raan (2004) by examining the annual number of citations of a publication in each year after it was published:

[2] In the current study, the "uncited paper" always refers to the publications which only have Period I, not the publications whose number of citations is zero.

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a) If the number of citations of a specific paper in the first year after its publication is fewer than 2, its state in the first year is I; otherwise, the state in the first year is II.

b) Given a particular year, and the state of a specific paper in the previous year is I. If the number of citations in this year is fewer than 2, the state in this year is I; otherwise, the state in this year is II.

c) Given a particular year, and the state of a specific paper in the previous year is II. If the number of citations in this year is 20% greater than that of the previous year, the state is II in this year; otherwise, the state is III.

d) Given a particular year, and the state of a specific paper in the previous year is III. If the number of citations in this year is equal to zero or is 10% smaller than that of the previous year, the state in this year is IV; otherwise, the state is III.

e) Given a particular year, and the state of a specific paper in the previous year is IV. If the number of citations in this year is 10% greater than that of the previous year, the state in this year is III; if the number is not 10% higher than that of the previous year and it is fewer than 2, the state in this year is V. If either of the two conditions is satisfied, the state in this year is still IV.

We adopt an iterative check to reduce the volatility as: If the state of the publication in the previous year is the same as that in the following year, the state in the current year would be adjusted to the same period.

Dataset

The dataset used in the current study comes from the Indiana University Network Science Institute (IUNI) in-house version Web of Science (WoS). It contains the bibliographic data of high-quality journals, conference articles, and monographs. Although the WoS is not exempt from limitations on its coverage (Mongeon & Paul-Haus, 2016; Moya et al., 2007), there are at least two reasons why we choose this dataset for our research. On the one hand, the WoS covers a variety of disciplines and a large

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amount of data at the international level; on the other hand, there is a long history in bibliometrics of using WoS for citation analyses (Waltman, 2016), and it is one of the most important databases for bibliometric studies and research assessment purposes (Iefremova et al., 2018; Li, Weng & Wang, 2021; Quan et al., 2017). We select all WoS papers published from 1970 to 1985, and set their citation window as 30 years[3].

Specifically, our dataset includes 10,517,699 distinct publications; among them, 893,647 distinct publications were published in 1985. These publications are labelled as one or more fields from 250+ subject categories from the classification system of Clarivate[4]. All of these 250+ subject categories are organized into six disciplines, namely *Arts & Humanities*, *Clinical, Pre-clinical & Health*, *Engineering & Technology*, *Life Sciences*, *Physical Sciences*, and *Social Sciences*. In our analyses, one publication may be classified into more than one discipline according to its labels; hence, the total number of individual publications is not exactly equal to the sum of the publications in the six disciplines. The numbers of publications under these six disciplines are shown in Table 1. Additionally, self-citations are not excluded in our dataset.

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Table 1. Number of publications in each discipline.

Discipline	# 1985_pubs (%)	#all_pubs(%)
Arts & Humanities	111,338 (12.46%)	1,118,583 (10.64%)
Clinical, Pre-Clinical & Health	253,723 (28.39%)	2,175,383 (20.68%)
Engineering & Technology	121,392 (13.58%)	1,397,192 (13.28%)
Life Sciences	216,489 (24.23%)	2,848,624 (27.08%)
Physical Sciences	179,562 (20.09%)	2,591,283 (24.64%)
Social Sciences	100,314 (11.23%)	1,313,063 (12.48%)

Note: “1985_pubs” means the documents published in 1985, a subset of our data; “all_pubs” refers to all publications in our dataset (from 1970-1985). “%” is calculated by dividing the #pubs of the discipline by the total number of individual publications.

[3] Some papers were published in January and some papers were published at the end of 1985. Thus, we select the data from 1985 to 2015 (including 2015) to ensure the citation window is not shorter than 30 years. This would lead some papers’ citation window to be close to 31 years. Yet, compared to the citation window, the nuance is so insignificant and we thus ignore it practically.

[4] http://help.prod-incites.com/inCites2Live/indicatorsGroup/aboutHandbook/appendix/mappingTable.html.

RESULTS

Overview

For the five-period framework as aforementioned, Period I represents the state when a paper has no or a few citations (the annual citation counts should be fewer than 2), and the following three periods (a.k.a., Periods II+III+IV) indicate that the paper starts to receive citations, regardless of its trends—increasing or decreasing. To this end, we particularly focus on the below two partitions, namely the lengths (number of years) of Period I (sleeping period, annotated as SP) and of Periods II+III+IV (recognition period, annotated as RP). Figure 2 present the distribution of length of SP and RP, respectively for each discipline[5].

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[5] The year of publication is stipulated as 0 instead of 1, and this is also applied for all the following analyses.

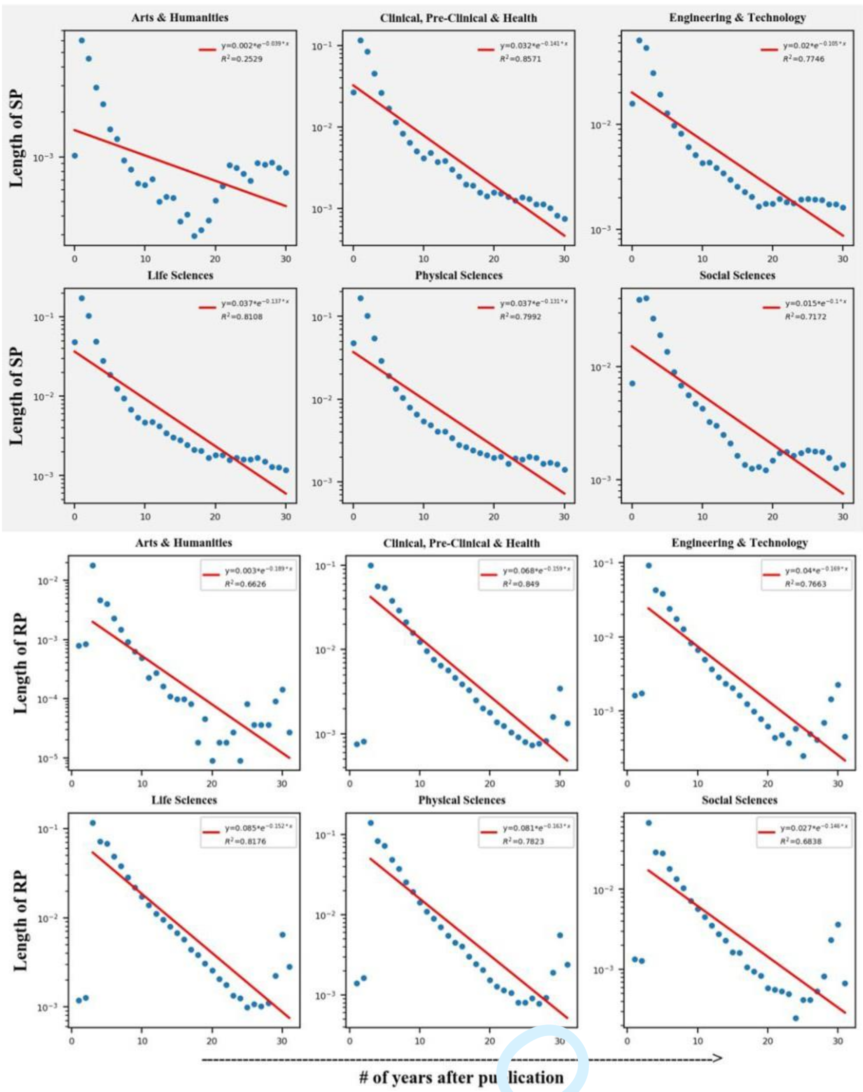

Figure 2. Distribution of the lengths of SP (the first two rows) and RP (the last two rows) by discipline.

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Some papers are always in Period I without entering the following period(s); these are often called "uncited papers" and they will not be included in the following analyses[6]. The x-axes in Figure 2 represent the length of SP (rows 1 and 2) or RP (rows 3 and 4), while the y-axes represent the probability. By fitting the distribution of SP length, we find that the distribution of SP conforms to negative exponential distribution for all disciplines except for *Arts & Humanities*. However, this may be attributable to

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[6]. We see from Figure 2 (rows 1 and 2) that the vertical value when the length of SP equals 31 is quite great. This is because we include all publications with 31-or-more-years SP as 31, leading to an unexpected leap beyond a long-tail distribution.

the huge number of uncited papers—we find that over 90% of publications in Arts & Humanities are uncited papers. Even though it suggests that most "cited papers" in those disciplines have a short SP and, with prolongation of SP, the number of papers decreases exponentially.

Similarly, we use several functions to fit the distribution of RP, as Figure 2 (rows 3 and 4) shows. The distribution of RP also conforms to a negative exponential distribution and it shows that most literatures have a short RP. Actually, it is worth noting that R^2 of the sub-figures in rows 3 and 4 is smaller than that in the first two rows. Yet, by analyzing Figure 2, we find that the difference mainly comes from the special dots (two outliers for all sub-figures in rows 3 and 4, lower-left). It can be considered that these outliers represent a special kind of literature called "early rise, rapid decline" (Aversa, 1985). These publications receive many citations rapidly after their publication—a short SP—and decline quickly after reaching their peak—a short RP. There are only a limited number of "early rise, rapid decline" papers, so the R^2 of the sub-figures in the last two rows of Figure 2 is not as good as that in the first two rows. Therefore, we exclude the two outliers in the function fitting for the distribution of RP (rows 3 and 4).

Regarding discipline-wise results, the basic descriptive statistics are shown in tables 2 and 3. For example, the mean of SP for *Clinical, Pre-Clinical & Health* is 3.98 and that of the RP is 6.96, which illustrates that, on average, the papers belonging to this discipline receive virtually no citations in the first four years after their publication and will tend to be cited in the following seven years (years 5 to 11). After that, the popularity of these papers drops dramatically and they will tend to receive very few citations.

Table 2. SP length of publications in different disciplines.

Discipline	*Mean*	*Q1*	*Q2*	*Q3*	*# pubs.*
Arts & Humanities	9.92	2	5	19	3952
Clinical, Pre-Clinical & Health	3.98	1	2	4	98679
Engineering & Technology	5.5	1	3	6	33351
Life Sciences	3.62	1	2	4	109039

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Physical Sciences	3.87	1	2	4	91980
Social Sciences	5.98	2	3	7	21310

Note: Publications that only have *Period I* are not included; Q1-Q3 are top 25%, 50%, and 75% of the values, respectively. The same below.

Table 3. RP length of publications in different disciplines.

Discipline	*Mean*	*Q1*	*Q2*	*Q3*	*# pubs.*
Arts & Humanities	4.66	3	3	5	3952
Clinical, Pre-Clinical & Health	6.96	3	5	8	98679
Engineering & Technology	6.04	3	4	7	33351
Life Sciences	7.36	4	5	9	109039
Physical Sciences	6.59	3	5	7	91980
Social Sciences	6.79	3	5	8	21310

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We can see that some disciplines' SP and RP are similar, such as the *Clinical, Pre-clinical & Health* and *Physical Sciences*, and both their mean values of SP are close to 4. We also observe some differences between the two average values, such as the Arts & Humanities (RP mean = 4.66) and Clinical, Pre-clinical & Health (RP mean = 6.96). To further explore inter-disciplinary differences of SP and RP, we employ the Kruskal-Wallis test (KW-test) to test the significance of their difference. KW-test is a nonparametric test for multiple samples and has a good applicability without limitation of distribution of samples. The distribution of data, SP and RP, does not conform to normal distribution; this is the main reason why we choose the KW-test. SPSS 25.0 is adopted to implement these analyses.

We present the KW-test from two perspectives, namely the whole samples without considering two specific disciplines' statistical differences (Table 4), and for all discipline pairs (Table 5). From Table 4, we can see that there are significant differences in the distributions of SP and RP lengths. Nonetheless, the result in Table 4 is only applicable for the whole disciplines, and we thus do not know the significance of differences for any two specific disciplines. To this end, Table 5 shows a discipline-wise comparison in which we see that the difference of distribution of SP length is significant and exists in any two disciplines; this is also the case for the distribution of

RP length. It verifies again the differences of obsolescence processes among science disciplines.

Table 4. KW-test for the whole disciplines. Two stars (**) represent *p* < 0.01.

Test	***Sig.***
KW-test for SP length	.000**
KW-test for RP length	.000**

Table 5. KW-test (*test statistic*) results of SP (bottom-left) and RP (top-right) lengths for discipline pairs.

Discipline	**AH**	**CPH**	**ET**	**LS**	**PS**	**SS**
AH	-	-66341.7**	-42062.5**	-73832.9**	-57364.4**	-52464.3**
CPH	65338.7**		24279.2**	-7491.2**	8977.3**	13877.4**
ET	42155.7**	-23183.1**	-	-31770.5**	-15302.0**	-10401.8**
LS	80215.1**	14876.4**	38059.5**	-	16468.5**	21368.6**
PS	74864.1**	9525.4**	32708.4**	-5351.0**	-	4900.1**
SS	26098.9**	-39239.9**	-16056.8**	-54116.3**	-48765.2**	-

Note: (1) Significance: *: p<0.05; **: p<0.01. (2) Abbreviations: *Arts & Humanities* (AH); *Clinical, Pre-Clinical & Health* (CPH); *Engineering & Technology* (ET); *Life Sciences* (LS); *Physical Sciences* (PS); and *Social Sciences* (SS). The same below.

Temporal characteristics

To more deeply explore SP and RP, we adopt a temporal analysis for the two stages. We calculate the mean values of SP and RP for all papers grouped by their publication years. The results are shown in Figure 3.

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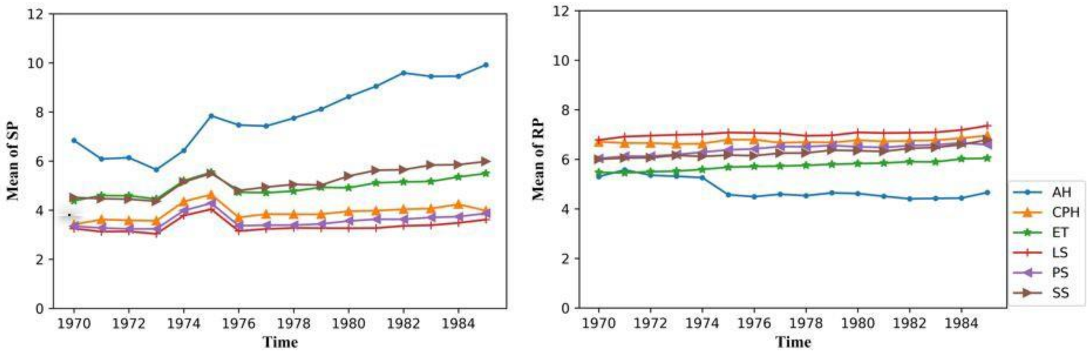

Figure 3. Temporal variation of SP (left) and RP (right).

We can see that the mean of SP for most disciplines had a slight increase during the time window except the SP of *Arts & Humanities*. The mean of SP for *Arts & Humanities* was decreasing from 1970 to 1973, and increased rapidly from 5.65 (in 1973) to 9.92 (in 1985). The change of SP of *Arts & Humanities* indicates that, on average, the literatures published in 1985 require almost double the amount of time to start their RP than earlier literatures. Similar results could be found in the temporal variation of RP for the six disciplines. However, the mean of RP for *Arts & Humanities* had a decrease instead of an increase during the time window, while the means of RP for other disciplines were stable.

We then sum SP and RP together, which measures the length of a paper's life-cycle (Periods I+II+III+IV). For example, a paper with a three-year-long SP and a five-year-long RP would be obsolescent ("dead") in the eighth year after its publication, and it also indicates that the length of this paper's life is eight years. The temporal variation of SP+RP is shown in Figure 4.

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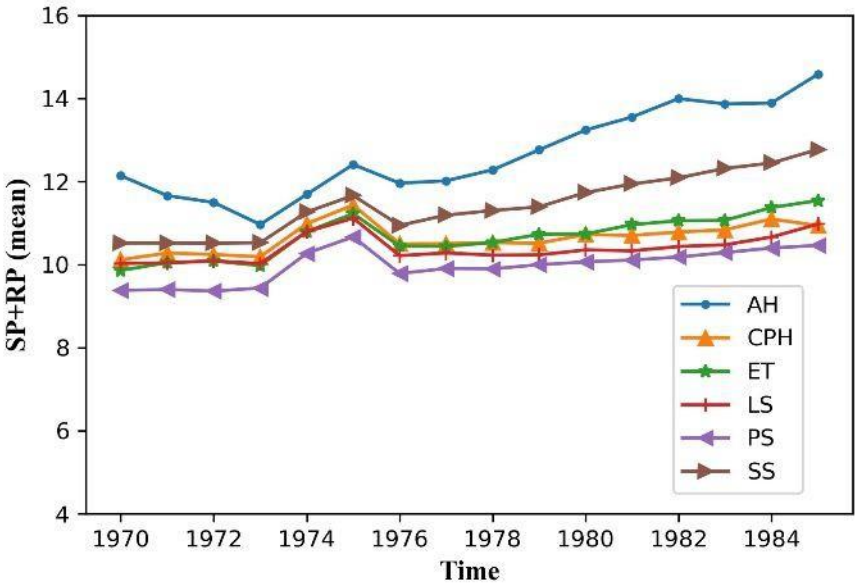

Figure 4. Temporal variation of "SP+RP" (i.e., Periods I+II+III+IV).

Figure 4 illustrates that the length of literatures' life extends a little bit, and those of *Clinical, Pre-Clinical & Health* (CPH), *Engineering & Technology* (ET), *Life Science* (LS), and *Physical Science* (PS) have a slight increase while those of *Arts & Humanities* (AH) and *Social Sciences* (SS) have a relatively significant growth. It also indicates that, for the papers of CPH, ET, LS, and PS, on average, they would be obsolescent around the tenth year after their publication, and the life-cycle of AH papers is longest, close to 15 years.

From the above analyses, we conclude that the two stages, SP and RP, remain almost unchanged for the papers from five of the six disciplines—except for AH—which could be used as an indicator to describe the obsolescence process or life-cycle of literatures, like the Half-Life indicator to the disciplines. In AH and SS, the length of a paper's life extends significantly, but an extended dataset covering more recent publications is needed to confirm this trend.

Citation count and obsolescence patterns

Citation curves are diverse among publications with various citation-based impacts, such as the highly cited publications and those with a few citations (Li & Ye, 2014).

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Therefore, we further explore how the obsolescence patterns may differ between publications with various citation counts. To this end, we partition the publications in 1985 into two groups, namely "Highly cited" (HC) and "Non-highly cited" (NHC) groups. The HC group consists of the top 1% publications with the greatest number of citations. We obtain the NHC group by selecting the publications with the top 1%-10% citations. This is partly because we observe from our dataset that there are only ~10% publications that receive sufficient citations to support an obsolescence pattern analysis (say 1 citation per year, leading to a total of 30 citations in a 30-year-long time window)[7].

We carry out a statistical analysis for SP and RP, and adopt KW-tests to check the significance of the difference for HC and NHC groups, respectively. The result indicates that the number of pairs with significant difference reduces with the increasing of citation counts.

As Tables 6 and 7 show, for the NHC group, there is one discipline pair, *Social Sciences* and *Engineering & Technology*, which is non-significant. Yet, for the HC group, there are five discipline pairs that do not show significant differences. It suggests that, in some cases, highly cited (top 1%) publications may share similar obsolescence features regardless of their disciplines and share a similar aging process. However, for most pairs, the differences between disciplines are still significant, which indicates that the growing number of citations diminishes the significance of the difference but does not eliminate it. We are also interested in the differences between HC and NHC groups. As the Mann-Whitney U test (MW-U test), a nonparametric test, is suitable for the test for two samples, we adopt it in the comparison between HC and NHC groups. Obviously, the differences between HC and NHC groups are significant (see Table 8), and this illustrates that the SP and RP can easily distinguish the publications with

[7] To ensure that HC publications strictly have more citations than the other 99%, we exclude publications from the HC group that have the same number of citations as other publications in the 99%. Thus, the number of HC publications may not exactly equal the 1% of the total number of all publications. This is also the case for NHC publications.

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different citation impact.

Table 6. KW-test (test statistic) results of SP (bottom-left) and RP (top-right) lengths for discipline pairs for the NHC group.

Discipline	AH	CPH	ET	LS	PS	SS
AH	-	-19074.4**	-11513.8**	-23083.6**	-16637.9**	-15782.0**
CPH	16893.1**	-	7560.7**	-4009.2**	2436.5**	3292.4**
ET	10058.1**	-6835.0**	-	-11569.9**	-5124.2**	-4268.3**
LS	20746.4**	3853.3**	10688.3**	-	6445.7**	7301.6**
PS	17734.1**	841.0**	7676.0**	-3012.3**	-	855.9*
SS	9218.9**	-7674.2**	**-839.2**	-11527.5**	-8515.2**	-

Note: *, p<0.05; **, p <0.01. The same below.

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Table 7. KW-test (test statistic) results of SP (bottom-left) and RP (top-right) lengths for discipline pairs for the HC group.

Discipline	AH	CPH	ET	LS	PS	SS
AH	-	-1878.3**	-1582.1**	-2224.8**	-2333.8**	-2206.4**
CPH	1634.7**	-	296.2**	-346.5**	-455.5**	-328.1**
ET	566.6**	-1068.0**	-	-642.7**	-751.7**	-624.3**
LS	2043.4**	408.8**	1476.8**	-	**-109.0**	**18.4**
PS	1562.0**	**-72.6**	995.4**	-481.4**	-	**127.4**
SS	659.3**	-939.3**	**128.7**	-1348.1**	-866.7**	-

Table 8. Mann-Whitney U test (Standardized test statistic) results of SP and RP for each discipline between HC and NHC groups.

Discipline	SP	RP
AH	11.216**	-14.725**
CPH	19.183**	-52.664**
ET	7.944**	-31.747**
LS	18.495**	-50.186**
PS	13.357**	-50.350**
SS	10.272**	-27.542**

Robustness check for operationalization

In the above empirical study, we operationalize the conceptual model and set the criteria for each rule as peer van Raan (2004). We also perform a robustness check to investigate how sensitive our results are to the operationalization rules. Thus, we make several alternative strategies according to the definition of “deep sleep” and “less deep sleep” for “sleeping beauties” and adjust the parameters (Table 9). After that, we duplicate the experiments and analyses with the new operationalization with all publications in 1985. The statistical results (mean values) for SP and RP with different strategies are shown in Table 10.

Table 9. The strategies for robustness check.

Strategy	Details of adjustment
A	In the rules (a), (b), and (e) in METHOD, all the integer values (number of citations) are adjusted to **3** from the original value **2**.
B	In the rules (a), (b), and (e) in METHOD, all the integer values (number of citations) are adjusted to **3** from the original value **2**; in rule (c), the **20%** is adjusted to **15%**; in rules (d) and (e), the **10%** is adjusted to **5%**.
C	In rule (c), the **20%** is adjusted to **25%**; in rules (d) and (e), the **10%** is adjusted to **15%**.
D	In rule (c), the **20%** is adjusted to **15%**; in rules (d) and (e), the **10%** is adjusted to **5%**.
E	All the integer values (number of citations) are adjusted to **3** from the original value **2**. In rule (c), the **20%** is adjusted to **25%**; in rules (d) and (e), the **10%** is adjusted to **15%**.

Notes: All the adjustments refer to the original rules in the METHODS section, if not mentioned in the current table; the other rules for these five strategies in the table are the same as the original rules in METHODS.

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Table 10. Mean values of SP and RP for each discipline with different strategies.

Discipline	SP(A)	RP(A)	SP(B)	RP(B)	SP(E)	RP(E)	# pubs (A,B,E)	SP(C)	RP(C)	SP(D)	RP(D)	# pubs (C,D)
AH	11.37	5.76	11.37	5.76	11.37	5.76	1423	9.92	4.66	9.92	4.66	3952
CPH	4.36	7.18	4.36	7.20	4.36	7.18	65646	3.98	6.96	3.98	6.96	98679
ET	6.55	6.52	6.55	6.53	6.55	6.52	19532	5.50	6.04	5.50	6.05	33351
LS	3.97	7.47	3.97	7.48	3.97	7.47	76809	3.62	7.36	3.62	7.36	109039
PS	4.46	6.80	4.46	6.82	4.46	6.80	60828	3.87	6.59	3.87	6.60	91980
SS	6.87	7.52	6.87	7.53	6.87	7.52	12502	5.98	6.79	5.98	6.80	21310

Note: #pubs does not include the publications which only have Period I. SP(A) represents the length of SP under the definition of Strategy A mentioned in Table 9.

We can see that the differences of the mean of SP and RP among strategies A, B, and E are nuanced, which is also the case for the comparison among strategies C, D, and the original strategy in the METHODS section (see also tables 2 and 3). It suggests the robustness of our operationalization, though the experimental results are relatively sensitive to the criteria referred to "**Deep sleep**" and "**Less deep sleep**" in "**Sleeping beauties**". As the criteria referred to as "Deep sleep" is so strict that it identifies more publications as "uncited paper", our operationalization in METHODS adopting "Less deep sleep" might be more pragmatic, as the threshold is not so strict, to encode the obsolescence process of publications.

An exploration: revival of literature

Inspiringly, we observe a special but crucial phenomenon from the citation curves of the publications—we call it "literature revival" —and these special publications will experience another life-cycle after obsolescence. This indicates that, although a certain publication has been "dead" (receiving almost no citations) for quite a long period, sometimes it is cited again by a very recent publication due to the influence from, say, the change in academic community or research field. This occasionally occurs when quite an old publication, though its citation life-cycle has ended already, is found to be invaluable for a new study and its following-up publications (citation). To explore the special phenomenon, we extend the above operationalization framework (METHODS, a-e) by adding a new rule:

f) Suppose that, for a particular year, the state of a specific paper in its previous year is Period V. If the number of citations in this year is greater than the 20% of the peak of its annual citations (if the peak value is fewer than 20, set it to 20), the state in this year is II; otherwise, the state in this year is V.

According to the new rule, the state change from Periods V to II of one paper is

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seen as revival. Thus, we count the frequency of revival of every paper (in 1985) and show its distribution in Figure 5.

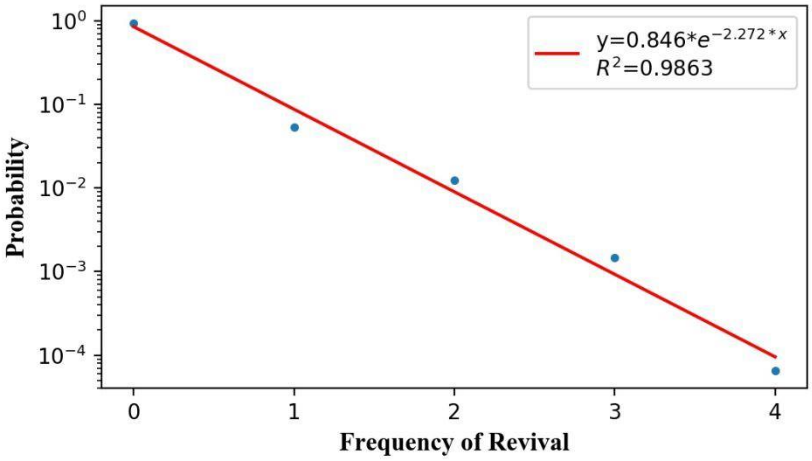

Figure 5. Distribution of frequency of revival with all 1985 publications.

According to Figure 5, the maximum of the frequency is 4, which indicates that these publications experience five life-cycles during the time window we examine. Most publications never "revive" as they have only one life-cycle. The distribution of frequency of revival conforms to a negative exponential distribution with $R^2 = 0.986$.

For each discipline, we calculate the mean number of revival times for all publications and for a subset of the data—the publications which experience at least one revival. The statistical results are listed in Table 11.

Table 11. Statistical results of revival for each discipline.

Discipline	Mean (one)	# pubs (one)	Mean (all)	# pubs (all)	one/all (%)
AH	1.24	433	0.004823	111338	0.389
CPH	1.21	17293	0.08	253723	6.816
ET	1.26	5767	0.06	121392	4.751
LS	1.22	20773	0.12	216489	9.595
PS	1.25	17050	0.12	179562	9.495
SS	1.28	4383	0.06	100314	4.369

Note: "**One**" represents the results for the publications which experience at least one revival—revived publications; "**all**" represents the results for all publications in 1985 (for each discipline); "**one/all**" is the proportion of the revived publications.

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We can see that the proportion of publications which experience revival has significant difference for the six disciplines. In *Life Sciences* (LS) and *Physical Sciences* (PS), the proportion is close to 10%, while in *Arts & Humanities* (AH), the proportion is the least, 0.389%, which indicates that, on average, there are only four papers experiencing revival in every thousand *Arts & Humanities* publications. This is probably due to the various proportions for the six disciplines: the mean values of frequency for all publications are significantly different; yet, such differences diminish for the revived publications.

Table 12 shows the KW-Test results of revival for discipline pairs where only the publications experiencing revival—revived publications—are included, as the differences among disciplines are obvious when considering all publications. Different from common sense, in which people observe a significant difference between *Arts & Humanities* and other disciplines (Reale et al., 2018; Weingart & Schwechheimer, 2007), the revival in *Arts & Humanities* has no significant difference from that in the other five disciplines when considering revived publications, especially the *Clinical, Pre-Clinical & Health*, *Engineering & Technology*, *Life Sciences*, and *Physical Sciences*. On the other hand, although the mean value for *Social Sciences* (1.28) is close to that for *Physical Sciences* (1.25), the difference is significant.

Table 12. KW-test (*test statistic*) results of revival for discipline pairs.

Discipline	AH	CPH	ET	LS	PS	SS
AH	-	-	-	-	-	-
CPH	955.253	-	-	-	-	-
ET	-242.669	-1197.932**	-	-	-	-
LS	838.429	-116.824	1081.099**	-	-	-
PS	-52.946	-1008.2**	189.732	-891.376**	-	-
SS	-1022.02	-1977.274**	-779.351	-1860.45**	-969.074**	-

Note: **, p<0.01.

In a word, revival is a special phenomenon for scientific publications which experience more than one life-cycle. Our pilot analysis shows that there is no significant

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difference for the revival phenomenon in *Arts & Humanities* and *Physical Sciences*, and several other pairs, which indicates that the revived publications in these fields may have some similarities in terms of obsolescence process.

DISCUSSION

In this study, we introduce a new micro-level conceptual model of literature aging. This model partitions the aging process of individual publications into several periods according to the citation rate. With this new model, we could see more details about literature aging from the perspective of individual publications, which outperforms the previous studies focusing on a set of publications—the macro level. To improve and apply this new conceptual model, we propose an additional period, supplementing the original partitions, to describe the whole process of aging, and offer a feasible operationalization for practice. Our study also highlights this contribution.

There are at least two ways of applying our operationalization. On the one hand, as shown in the current paper, researchers can purely encode the aging process of literature and characterize the lengths of SP (Period I) and RP (Periods II+III+IV), or some other Periods, as an easier strategy to explore literature aging; this strategy particularly functions when the number of focal publications is great. On the other hand, as citations are at the basis of several quantitative measures increasingly used in evaluation criteria aimed at evaluating the career trajectories of scholars (Edwards & Roy, 2017) and the research performance of institutions (Bornmann, Haunschild, & Mutzm, 2020; Li et al., 2017), bibliometricians and research evaluators could quantify the lengths of each individual period one by one and present a more nuanced picture of each obsolescence process. That will show more accurate details in the research evaluation. Finally, it is necessary for us to exploit the "literature revival" deeply, which will help to understand more about the laws of literature aging.

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SP and scientific evaluation

Extant studies have argued that publications' citation maturity times vary for each discipline and different publication types (Diodato & Smith, 1993; Radicchi et al., 2008; Wang, 2013); the citation curves could be classified into several groups (Chakraborty & Nandi, 2018). This might be the most important factor determining the effectiveness of cross-discipline evaluation. For example, the two-year Journal Impact Factor (JIF) indicator might be unfeasible to evaluate academic journals of these fields whose citation maturity time is five years. Some scholars have been aware of the negative impact of various citation maturity times for cross-discipline scientific evaluation when observing the evaluative indicators such as JIF. For instance, Huang et al. (2012) proposed normalized impact indicator considering article life span in journal ranking. Jacsó (2009) suggested that the two-year time window for JIF is too short to evaluate effectively the fields whose citation maturity time is hysteretic, and argued that a five-year time window (5-JIF) is needed to supplement the original JIF. Glänzel, Schlemmer and Thijs (2003) argued that, in the theoretical fields, a citation window larger than three years should be applied. Additionally, Sombatsompop et al. (2004) and Rousseau (2005) suggested setting various time windows for different disciplines. Particularly, Sombatsompop et al. (2004) preferred using the "Cited Half-Life" of journals to determine the length of time window to the fixed two-year time period of the original JIF indicator. Whilst continuous efforts have been made, the core issue has not been resolved—people tend to ignore the variability of the time when publications start to receive citations. If the publications in a certain field generally need to wait for five years before they start receiving citations, the JIF is not feasible to evaluate these publications as it contains the early low-citation period. Different from these explorations, Dorta-González (2013) improved the JIF from another perspective by proposing the two-year maximum journal impact factor (2M-JIF); his core idea is to use a rolling time window to replace the fixed time window of the JIF and select the maximum value of JIF among multiple years. The contribution of the 2M-JIF is that it

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ensures the time window used in calculation must contain the mature period of that journal.

SP can function as an improvement of the JIF and its variants. SP represents the low-citation period before a publication reaches its mature time. Thus, by introducing SP into the JIF, one can make sure that the time window contains and only contains the mature period of that one publication. Specifically, we can set the JIF time window as a "spacing window" according to SP. For example, if we aim to evaluate the JIF in 2015 of one specific journal in *Social Sciences*, we should collect citation data of this journal in 2008 and 2009—instead of 2013 and 2014—as the mean of the SP of *Social Sciences* is 6 (see Table 2); such a strategy excludes the "sleeping period" which cannot demonstrate the real citation-based impact as the publications are waiting to be cited. It would be fairer for these publications whose mature period is delayed when using the evaluative indicators improved by SP. On the other hand, compared to the 2M-JIF, JIF improved by SP characterizes the mature period, not peak, of the journals, which reveals the true impact of the journals in different years.

RP and scientific evaluation

There is another issue when we improve the evaluative indicator, such as JIF, by extending the time window. Take the 5JIF indicator as an example: Suppose that there are two journals belonging to different fields, A and B, respectively. The aging rate of publications in field A is fast with the RP length equaling 2, and that of publications in field B is relatively slow (RP length = 4). The length of SP in both fields is equal to zero. Thus, when we adopt the 5JIF to evaluate the two journals, the result is biased to both journals: To A, the five-year time window includes a two-year-long highly cited period, the RP, and a three-year-long period with very few citations (the "death" period after RP); however, there is only a one-year-long period with few citations included in the evaluation for field B with 5JIF. Therefore, the mean value of citations is distorted with the systematic deviation.

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The RP provides another approach to supplement JIF and variants. RP represents the mature period of publications' citations, and it offers clues to set a proper time window for evaluative indicators according to the features of publications from various research fields. For example, we should set a short time window for the disciplines with small RP value. In that case, the indicator evaluates the impact of publications during their highly cited period, which makes it more comparable for the evaluation results for different disciplines.

Different from JIF and variants that focus on short-term impact, RP inspires us to explore the "long-term impact" of scientific publications (Wang, Song & Barabási, 2013). However, there is not an exact definition about the "long term." With the help of the RP stage, we try to define the long-term impact as the impact around the end of RP. For instance, if the mean of SP of one field is 2 and its mean of RP is 5, we may say that the impact around seven years after publication could be seen as the long-term impact of the publications in this field. For a field with longer SP and RP, the length of the time window for "long-term impact" also varies.

SP and RP also open up many practical-oriented questions. For instance, in some cases, the median may be a better choice than the mean value of SP/RP, depending on the distributions of SP/RP and the purpose. As mean values are more sensitive to the outlier/extremum, which could show more tiny differences among disciplines, we only adopt the mean values in our analyses for SP/RP. Instead, when aiming to obtain a stable value/result, for example, to decide a year limit (according to RP) to remove the obsolescent literatures in a library, the median value might be a better choice as it is less affected by the distribution. On the other hand, our pilot study focuses on the six disciplines, but the sub-disciplines under each discipline are also different from each other. Thus, it is sometimes necessary to obtain the length of SP and RP for some sub-disciplines, to guarantee the validity and accuracy of the two measurements.

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A special phenomenon: Literature revival

When analyzing the aging process of literature, we find that some special publications would be cited again after their obsolescence and experience another life-cycle, which is named "literature revival". Though observed by a few studies (Li & Ye, 2014; Chakraborty & Nandi, 2018), little attention is paid to this special phenomenon. The revival phenomenon suggests that some publications do not conform to the common literature-aging models. Statistical analyses show that there exist significant difference between several discipline pairs. For the publications belonging to *Arts & Humanities*, revival is rare as the proportion of revived publications is only 0.389%. However, revival is common for the publications in *Life Sciences* and *Physical Sciences*, where the proportion is close to 10%, a non-negligible part of the overall literatures.

The revival indicates that the citation-based impact of some publications might be underestimated. The revived publications share several common features with the special literatures called "sleeping beauties". As the "sleeping beauties" are discovered and highly cited after a long sleeping period with few citations, their impact or academic contribution may not be evaluated fairly by conventional indicators, such as JIF. This is also the case for revived publications that experience another life-cycle after their "death". As conventional indicators only focus on the first life-cycle, the impact or contribution of revived publications would be underestimated as their following life-cycle, especially the highly cited period, is ignored. Therefore, more comprehensive, cross-disciplinary, and longitudinal studies are needed for this special phenomenon.

SP and RP for collection development in libraries

We all need a library! It is one of the most important institutions in modern society which preserves the achievements of civilization and provides services relating to knowledge. However, with the rapid growth of scientific publications, libraries cannot collect all publications as their collection space and funds are limited. Hence, libraries

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need to eliminate some out-of-date publications when gathering new literatures to control the scale of their collections. As such, the theories about literature obsolescence and the use of databases for the development of a collection strategy are crucial for guiding libraries to carry out elimination in a reasonable way. For instance, Yu-Bin et al. (2013) introduced the idea of literature aging to the studies on recommendation algorithms, which is helpful for librarians to recommend timely and topically correlated information resource to users. This study could serve as an example in applying its fruits in practice, including the collection development of libraries, and bringing together librarians and researchers based on previous efforts (Fosmire, 2004; Sangam, 1999).

LIMITATIONS AND FUTURE WORK

There are several limitations regarding the current paper. For example, when counting the citations received by one publication, self-citations are not excluded in our analyses. As self-citations may occur on purpose to raise the visibility of an author's previous study, this inclusion may result in some deviations between the citations curve used in our encoding processing and the citations curve without self-citations—and the latter has been thought to be a better choice in some studies (e.g., Costas, van Leeuwen & Bordons, 2010; Hirsch, 2005). Additionally, in our classification framework, one publication might be classified into more than one discipline, which may also influence the results with an aggregation at discipline level.

Another obvious limitation is that we define a set of arbitrary thresholds of operationalization rules. Using parameter-free indicator for the threshold is an ideal choice, like the beauty-coefficient proposed by Ke et al. (2015) for identifying "sleeping beauties". However, our operationalization aims at encoding the whole citation life with various citation patterns, not just one particular citation pattern like "sleeping beauties", which might be challenging to be defined by a single parameter or parameter-free indicator(s). In this study, we take a robustness check for our

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operationalization to reduce the impact of manual work. In any case, one of the most important tasks in future work is to improve the operationalization rules.

Moreover, in our experiments, we do not quantify the length of Periods I to IV one by one. Instead, we mainly focus on two stages, SP and RP. Therefore, we are going to implement more detailed analyses on each period and other partitions. Meanwhile, more sophisticated strategies, such as advanced time series analysis, are also needed in the future supplementary analyses. Furthermore, the discussion on the implications of SP and RP is insufficient; future studies could utilize real-world empirical datasets to examine the effectiveness of the improvement of original evaluative indicators (with SP and RP).

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