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Study of biomimetics applied to logistics, material handling, SCM and manufacturing: A bibliometric analysis (1990-2013)

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Biomimetics and logistics have been discussed broadly in the scientific literature with regard to their particular discipline. The main purpose of this paper is to explore the amount and structure of the scientific research on the interdisciplinary topic of biomimetics applied to logistics. With this subject area, we performed a query of scientific online databases and conducted a bibliometric analysis to explore the most influential works and their impact on logistics. However, the term bionics was introduced in the late 1960s, and our analysis revealed a marginal scientific attention on the combined topic bionics & logistics until 2003. Nevertheless, the interdisciplinary topic was increasing disproportionately until today in comparison to their particular disciplines. Additionally, the results of our analysis indicate that some fields of logistics benefit a lot from principles of nature (e.g. transport logistics from behavioural biology) while other fields of logistics could not use this potential. Furthermore, our analysis presents a country ranking according to the amount of publications, which is led by China. Finally, contents and findings are briefly discussed to provide an overview of the previous academic research.

[Keywords: bionics; biomimetics; logistics; material handling; SCM; bibliometric study; literature review]

1 INTRODUCTION AND AIM OF THE INVESTIGATION

Due to globalisation, dynamics of the markets, increasing clockspeed and ever faster dissemination of new technologies, requirements for existing logistics and production systems have changed. The existing approach for dealing with this problem is often to increase flexibility [1]. It describes the quick possibility of adapting systems within a strict pre-defined range without the need of large additional investments. Nevertheless, the turbulence of the business environment varies greatly, thus the dimension and direction of changes are hardly predictable. Here the approach of changeability tries to extend by integrating the terms flexibility and reconfigurability [2]. But it is obvious to the involved companies and countries that those who adapt faster to market requirements while keeping costs low, will be on the winning side. Therefore, scientists work hard to find successful approaches for solving complex problems in engineering and other disciplines mentioned above.

Throwing a glance at nature, also known as bionics or biomimetics, could be such a promising approach. Von Gleich et al. defines the term biomimetics as follows: "…learn from nature…investigation of natural…structures, functions, processes, and systems" [3]. A well-known example is the lotus effect of the lotus plant, which can be found in many products e.g., soil-repellent textiles [4]. In logistics, also, there are already several applications of biomimetics [5]. For example, transportation routes can be optimized by means of an ant algorithm [6]. And especially these associations between biomimetics & logistics will be illuminated in this article, while considering the following exciting questions: To what extent has biomimetics already been expanded into logistics? Which research categories are of major interest for the scientific community? Which trends have emerged in recent years in this combined interdisciplinary area? And how has the amount of publications increased compared with other disciplines? Which country actually leads the competition in finding successful approaches derived from biomimetics? Before all these questions are answered in Chapter 3, Chapter 2 will first draw attention to the used method and explain it further.

2 METHOD OF THE INVESTIGATION

To identify developments in various fields of science, bibliometrics has become a useful tool. The word consists of "biblio" referring to books, and "metrics" referring to measurement. Therefore, bibliometrics is a generic term for a whole range of specific measurements and indicators and can be understand as a set of tools for analysing publication data. For example: counting papers with attribution by country; counting citations to measure the impact of published work on the scientific community etc. [7, 8].

Before presenting the results in Chapter 3, this Chapter will consider the scope of the investigation, the data source determination and data collection and check.

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2.1 SCOPE OF THE INVESTIGATION

In a first step, the area of scientific investigation has to be marked out. For example, a study from the year 2010 is concerned with trends of biomimetics and its future potentials [3]. While Von Gleich's research contains an overall viewpoint of biomimetics, the focus of this study was specifically on biomimetics in logistics and related disciplines.

It was therefore necessary to construct different query couples as a search term to cover the "world" of biomimetics as well as the "world" of logistics. Literature provides a range of synonyms for biomimetics, which were used as search terms, including biomimetic, bionic, bio, and bio-inspired. These terms, which were complemented with definition, are also often used in literature for topics relating to biomimetics: self-organisation, swarm intelligence, ant algorithm and bee algorithm [5, 9, 10]. The search words for logistics included a broad range of terms like, logistic, transport, production system, manufacturing system, manufacturing, supply chain, shop floor, factory layout, material handling and material flow. Query couples like bio-inspired & logistic, bionic & material flow, self-organisation & logistic and other similar combinations were constructed from these words (see more in Table 1).

Table 1. Query couples.

query couples	
bionic & logistic	bio-inspired & logistic
biomimetic & logistic	swarm intelligence & logistic
bionic & transport	swarm intelligence & transport
self-organisation & logistic	swarm intelligence & supply chain
bionic & production system	swarm intelligence & material handling
bionic & manufacturing system	ant algorithm & logistic
bionic & manufacturing	ant algorithm & transport
bionic & supply chain	ant algorithm & supply chain
bionic & shop floor	ant algorithm & material handling
bio & factory layout	bee algorithm & logistic
bionic & material flow	bee algorithm & transport
biomimetic & material flow	bee algorithm & supply chain
bionic & material handling	bee algorithm & material handling
biomimetic & material handling	
bio inspired & material handling	

2.2 DATA SOURCE DETERMINATION

Databases are the basic building blocks of bibliometrics. Before a database can be used, it must be checked for suitability. Suitable criteria include time horizon, scientific fields, media forms, actuality and completeness. Today, there are three major state-of-the-art bibliographic databases with online access: Web of Science (WOS), Scopus and Google Scholar. Free data collection from Google is not available for serious scientific bibliometric analysis, because it is not completely clear which publications are recognized and how the citation is created [11]. With approx. 50 million entries, Web of Science and Scopus are relatively similar with regard to the quantity of their data. However, there are some differentiations in terms of content (see Table 2) [12].

In order to ensure the widest possible coverage of the area of investigation, the queries of the present study are evaluated in both databases.

Table 2. Database overview

	Web of Science	Scopus
content journals	12,000 journals	21,000 journals (of which 2,600 are Open Access)
content conferences	5.2 million articles	5.5 million articles of journals and conference records
content patents	42 million patents of "Derwent World Patent Index"	24.8 patents of 5 patent offices
amount of data	46 million entries	50 million entries
period of the collection	since 1900	since 1823
update	weekly	daily
period of the citation-collection	since 1900	since 1995
coverage	worldwide with Anglo-American orientation	worldwide with European orientation
literature management	EndNote, RefWorks, BibTex a.o.	EndNote, RefWorks, BibTex a.o.

2.3 DATA COLLECTION AND DATA CHECK

The queries in the databases were carried out between 3 Feb 2014 and 14 Feb 2014. To restrict the search and to obtain useful data, the following operators or limitations were used: The Boolean operator 'AND' between the terms of logistics and biomimetics. Furthermore, in the Web of Science Core Collection, the expression 'NEAR/2' was applied with shared biomimetical or logistical terms. Here, the searching field 'topic' includes title, abstract, author keywords and keywords plus. In the Scopus database, the expression 'PRE/2' was applied with shared biomimetical or logistical terms. The searching field contained article headlining, abstract and keywords. The operators NEAR/2 and PRE/2 automatically sort out documents, with more than two words standing between both parts of the search word (for example: "ant NEAR/2 algorithm AND logistic").

The received data was checked by using the summary concerning subject areas and sorted out if necessary. The criterion was whether or not the publications refer to economics and engineering sciences which are connected to logistics. For more detailed evaluations, the publications were divided into biological and technical sub-groups (e.g., behavioural biology, transport logistics, etc.) by means of the software Endnote. An automated check removed all duplicates. Afterwards, the citations of the publications were evaluated. On this occasion, an inspection of topic and duplicate took place, but without assigning the publications to individual subgroups.

3 ANALYSIS AND INTERPRETATION

3.1 OUTPUT ANALYSIS

This kind of investigation deals with the measurement of the scientific output considering scientific publications

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focusing on different details: for example, output from one person, output of an institute or university or a scientific subdiscipline concerning a certain time period, from which conclusions can be drawn about the productiveness regarding publications [8].

The evaluation of the present study contains 664 datasets in which 364 publications were determined and grouped directly by searching in WOS or Scopus. The remaining records are related to the citations of the examined publications. The results include three groups of publications: monographs, conference papers and journal articles. With 42 % journal articles, 31 % conference papers and 27 % monographs, the literature spectrum (Figure 1) indicates an almost equal distribution.

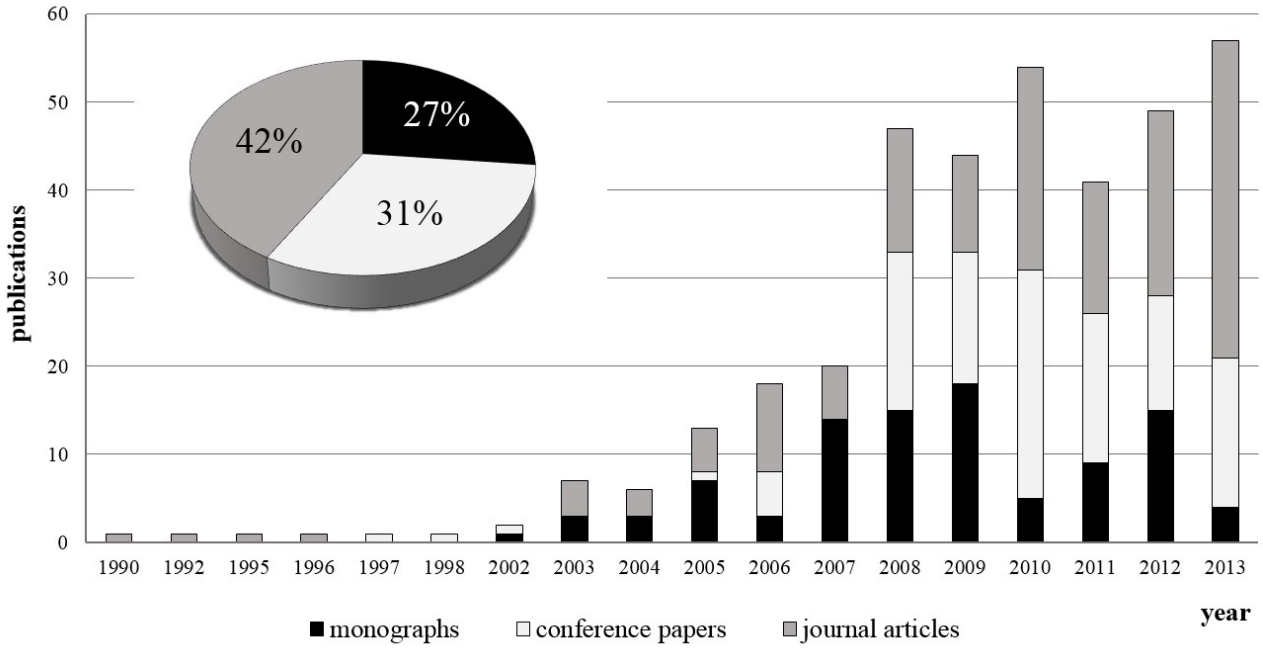

Figure 1. Literature spectrum.

As seen in Figure 1, the publication dynamic is very low till 2003 (≤2 publications p.a.). In the period between 1990 and 2002, only eight journal articles or conference papers were published in the area of biomimetics & logistics. But beginning with 2008 (47 publications), rapid growth can be observed on this connected topic. In a comparable study, Lepora et al. (2013) also draw a similar picture by focusing only on the term biomimetics and analysing publications from 1995-2011. While the amount of publications is very low from 1995 until 2002 (< 400 publications p.a.), it then increases significantly until 2011 with (2800 publications p.a.) [10].

The 364 analysed publications were released in 275 different mediums (journals, conferences etc.). This shows that the topic is very widespread, but some major journals and conferences were also detected (compare Appendix 1). So the journals with the most contributions were: International Journal of Production Research (IJPR) with 9 publications, followed by International Journal of Advanced Manufacturing Technology (IJoAMT) with 8 publications. Computer Integrated Manufacturing Systems (CIMS) and Expert Systems with Applications (ESWA) have each 5 publications and System Engineering Theory and Practice (SETaP) 4 publications. All other journals have ≤3 publications.

A similar picture emerges within conferences. The International Conference of Chinese Logistics and Transportation Professionals – Logistics (ICCLTP) leads with 7 publications followed by Mexican International Conference on Artificial Intelligence (MICAI), International Conference of Logistics Engineering and Management (ICLEM) and International Conference on Automation and Logistics (ICAL) with 3 publications each. All other conferences have ≤ 2 publications.

3.2 RESONANCE ANALYSIS

The following perception analysis deals with the resonance evoked by publications in the scientific community. For measuring purposes, the citation rate (CCP) describing the number of citations per publication is counted. The quality of a paper is determined by using this citation frequency. However, in bibliometrics, the so-called Matthew effect suggests that articles which could exceed a certain perception threshold are cited more often, while other comparable ones disappear. It can also be deduced with high

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probability that the more often known authors are cited, the better known they become [13].

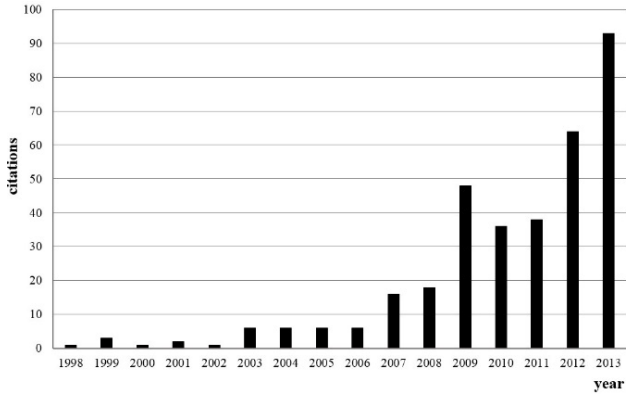

Figure 2. Citations per year

Figure 2 gives a similar picture as Figure 1. Until 2003, the citation of publications remains very low (eight citations in total from 1998 to 2002). Starting from 2009 (48 citations) there is a sudden increase of citations. This could be explained by the fact that there had been a strong increase in the quantity of publications the year before. This shows the close relationship between publication and citation behaviour. With the help of this graphical analysis, a strong growth dynamic over the past five years can be found in the field of 'logistics with biomimetics'.

When observing Figure 2, the following questions arise: which are the most frequently cited papers? Who are their authors? What are they dealing with? Appendix 2 answers with a compact overview, but the contents of the five most cited papers are described below in more detail.

The most frequently cited paper (36 citations) of our bibliometric analysis was published from Solimanpur, Vrat and Shankar in 2005. It deals with the development of an ant algorithm for solving the single row layout problem (SRLP). This new approach shows a better performance than many existing algorithms in this area [14]. In the fourth placed paper (23 citations) McKendall and Shang developed something similar: A hybrid ant systems (HASs) for solving the dynamic facility layout problem (DFLP). In a test with two data sets from the literature the HASs found new best solutions for more than one-half of all the test problems and was a more efficient technique for solving DFLP [15].

With 34 citations, Tharumarajah, Wells and Nemes (1996) provided the second most frequently cited paper. Because of customers' individual needs, a strong reduction of batch sizes is expected in the production area. Innovative biological structures instead of current organizations are discussed. Their work describes the underlying principle of three concepts: bionic, fractal and holonic manufacturing. In addition, design and operating characteristics are compared [16]. In their 1998 contribution, the same authors continue (8th place of our analysis) with 'biological manufacturing system', 'fractal factory' and 'holonic manufacturing'. They present different parallels between manufacturing systems and biological systems in terms of autonomous and spontaneous behaviour, social harmony and hierarchical relations. Manufacturing units could act, for example, as a cell to link up hierarchical control structures like shops, factories or companies [17].

The third most frequently cited paper that was quoted by 23 scientific publications was published by Chen and Ting (2006). It deals with algorithms for solving the vehicle routing problem. The authors improved the standard ACS (ant colony system) to the IACS (improved ant colony system) by adding the 'new state transition rule', the 'new pheromone updating rule' and diverse 'local search approaches'. In order to show improvements Chen and Ting (2006) applied the IACS on fourteen benchmark problems and compared the results with AS (ant system) and SA (simulated annealing). In eight of fourteen cases, IACS achieved the best results [18]. The 6th-placed paper by Fuellerer et al. (2009) deals with the related area of 'two dimensional loading vehicle routing problem'. In 2L-CVRP (two-dimensional loading capacitated vehicle routing problem) a heuristics procedure based on ACO (ant colony optimization) is applied. The ACO procedure is extended by a 'loading heuristics'. The algorithm can thus look for routes while checking at the same time whether the loading problem can be solved for the found distances [19].

Another field of activity (traffic logistics) considered by Lammer and Helbing (2008) received twelve citations. The authors introduced a control algorithm based on short-term traffic forecasts which enables coordination between neighbouring traffic lights. In this case, Lammer and Helbing (2008) tried to minimize the travel time (especially in urban areas) through appropriate traffic light control. This decentralised control algorithm stabilises the traffic as long as a stable 'fix-timed control with cycletime T' is given. Then 'the self-organized traffic light control' is applied to different traffic volumes. Additionally, the authors applied 'the self-organized traffic light control' to multiple traffic volumes. In nearly all cases, the model led to a reduction of travel time, subsequently also decreasing fuel consumption and CO2 – emissions [20].

3.3 COUNTRY RANKING

It is hard to interpret absolute figures on their output and response without other comparison values. A direct comparison with other people, universities or countries can help to detect additional information. Hence, the publications of our analysis were categorized to the respective countries. If author's affiliation were from different countries, those countries were included. Figure 3 shows a country ranking of all publications analysed in the database.

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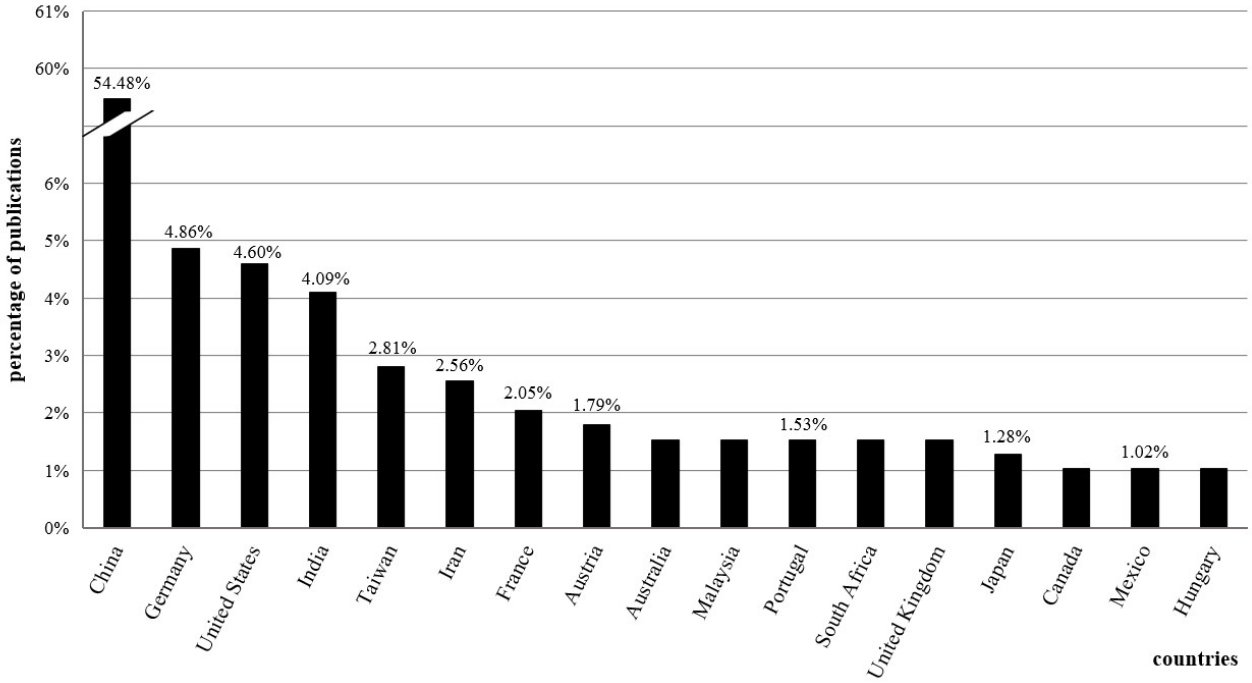

Figure 3. Ranking of countries with respect to publications focusing on the connected topic biomimetics & logistics (24 further countries, which are not shown in the figure, contribute a total amount of 10.74%)

China leads this comparison with a score of 54.48% contributing more than half of total publications. Germany follows with 4.86% and United States are third with 4.60%.

However, it should be noted that our analysis focuses on quantitative data and not on qualitative reviews of publications, nor does it consider other comparison values (research budget, number of scientists and universities, etc.). Nevertheless, a recent study of Von Gleich et al. (2010) considered publications between 1995 and 2005 with the keywords 'bionic*' and 'biomim*' (in contrast to our study, Von Gleich has no special focus on logistics). Thus the publications' distribution by countries was different to ours. Their ranking within the field of biomimetics was led by USA (32.5%), followed by Japan (12.16 %), Germany (9.57%) and China (7.59%) in fourth place [3]. However, the leading country in the combined subject of logistics and biomimetics, concerning research activities, is obviously China.

3.4 TREND ANALYSIS

Based on the obtained data, an attempt was made to determine potential scientific conceptual trends by observing a statistically detectable development. If certain issues in terms of publications remain at a highly increasing level for a longer time period, this is a positive trend (uptrend). The other way round, dropping citation rates reveal a decreasing subject interest (downtrend). Trend analysis serves strategic and political decisions in the field of science [8].

As seen in Figure 1, the number of publications has increased in the connected field of bionics & logistics since 2003. Since 2008, a fast growing amount of publications on the topic of bionics in logistics can be observed. Even if the dynamic of citation is added, a trend is clearly evident in this area.

Figure 4 compares publication dynamics, most essentially, the topic logistics (in Web of Science and Scopus) and the topic bionics (in Web of Science and Scopus) with the combined results of bionics & logistics. The starting point is in 2002, because publications had increased in the field of bionics & logistics from then on (see Figure 1). Publication behaviour in the topics mentioned is growing slightly overall, but not as strongly as in the combined area of bionics & logistics. In 2013 (52) in the area of bionics & logistics, 26 times more publications were published than in 2002 (2) compared with bionics, where only 5 times more publications had been published during the same period of time (2002:(123); 2013: (662)). In other words, from 2002 to 2013, the average rise for logistics is 12.06% p.a , 16.53% p.a for bionics and 34.51% p.a for bionics & logistics. This data shows that there is a trend towards biomimetic solutions in logistics.

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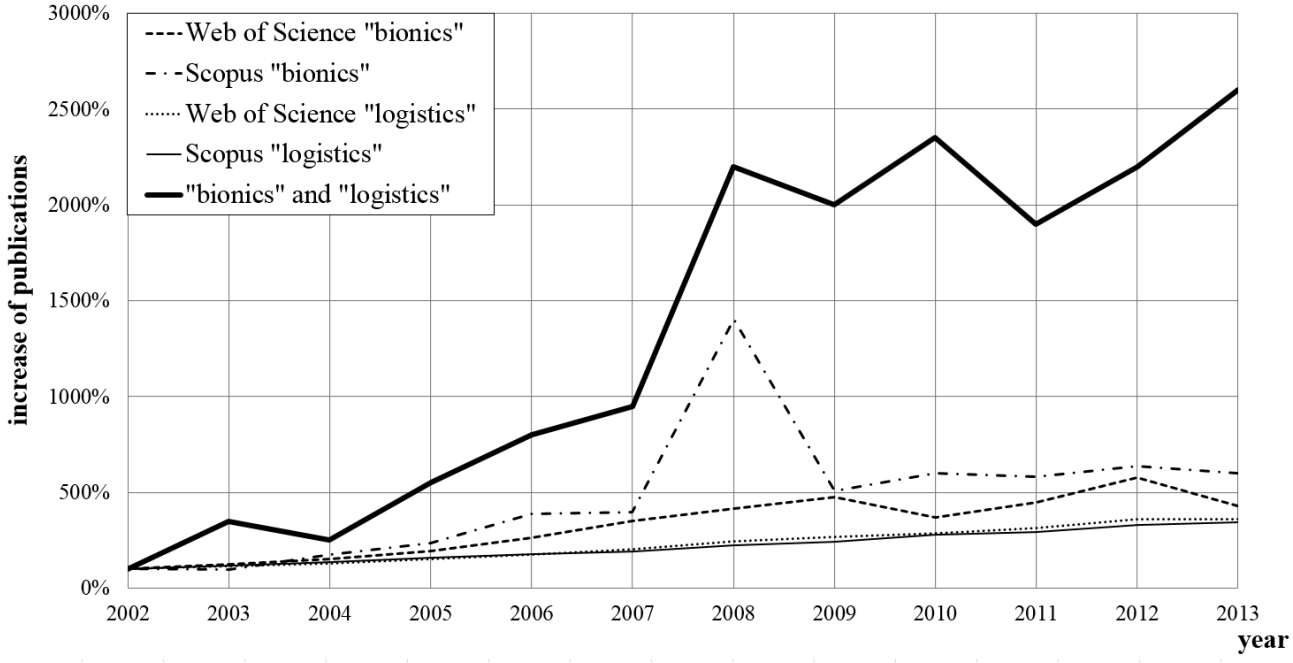

Figure 4. Comparison of publication dynamics in logistics, bionics and the combination of bionics & logistic

3.5 FIELD ANALYSIS

In the present study two scientific disciplines were taken into consideration: logistics and bionics. But due to the fact that those two fields are widespread and contain various research fields, a division into major categories was necessary for a more detailed overview.

By analysing the summary, the publications were grouped and categorized into the most important biological related fields of research on the one hand, while on the other hand they were divided into the major logistics related fields of research

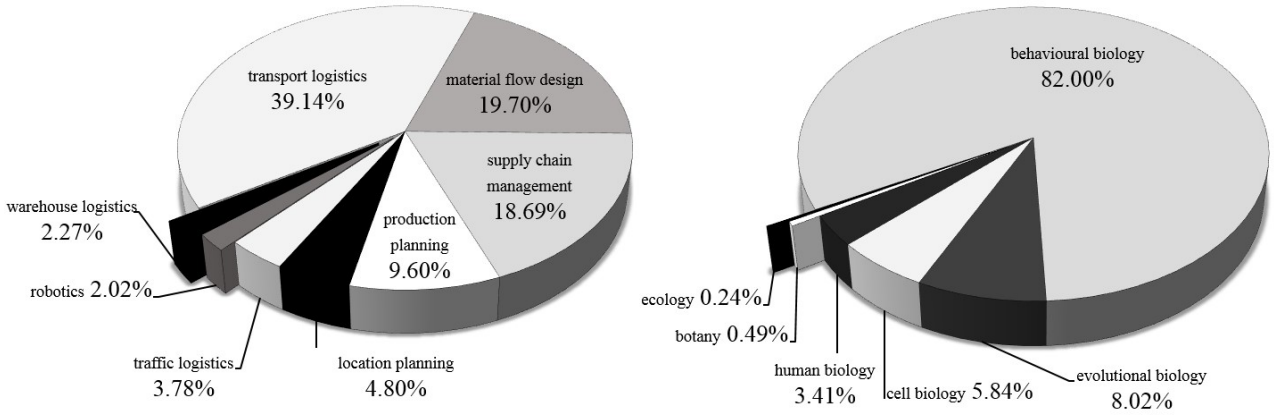

Figure 5. Distribution of the analysed publications within logistical fields of research (left) and biological fields of research (right)

The categories were developed step by step while analysing the publications. Therefore, there was no need for an "others" category. Figure 5 illustrates this categorization, where on the left side the distribution of the publications within logistical categories can be observed, while on the right side, the categorization regarding subdisciplines of biology can be seen. How we distinguished the logistics categories in detail can be studied in Appendix 3. The biggest portion in logistics (compare Figure 5 left) is transport logistics with 39.14% of the analysed publications, followed by material flow design with 19.70% and supply chain management with 18.69%. In the biological division (compare Figure 5 right), 82.00% of publications are assigned to behavioural biology (explores, describes and compares the behaviour of individuals and species) followed by evolutional biology (concerned with the study of evolutionary processes)

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with 8.02 % and cell biology (explores cells – their physiological properties, their structure, interactions with their environment etc.) with 5.84%. Some publications contained overlapping topics, so they were assigned to multiple subject areas.

To visualize the connection between different fields of research in bionics & logistics the results are compiled in a matrix (see Figure 6). Obviously, the areas of behavioural biology and transport logistics have the biggest overlap and therefore the most publications. Furthermore, behavioural biology is related to all the illustrated logistic topics, while other topics like robotics have not any intersection with botany, cell biology, evolutional biology and ecology.

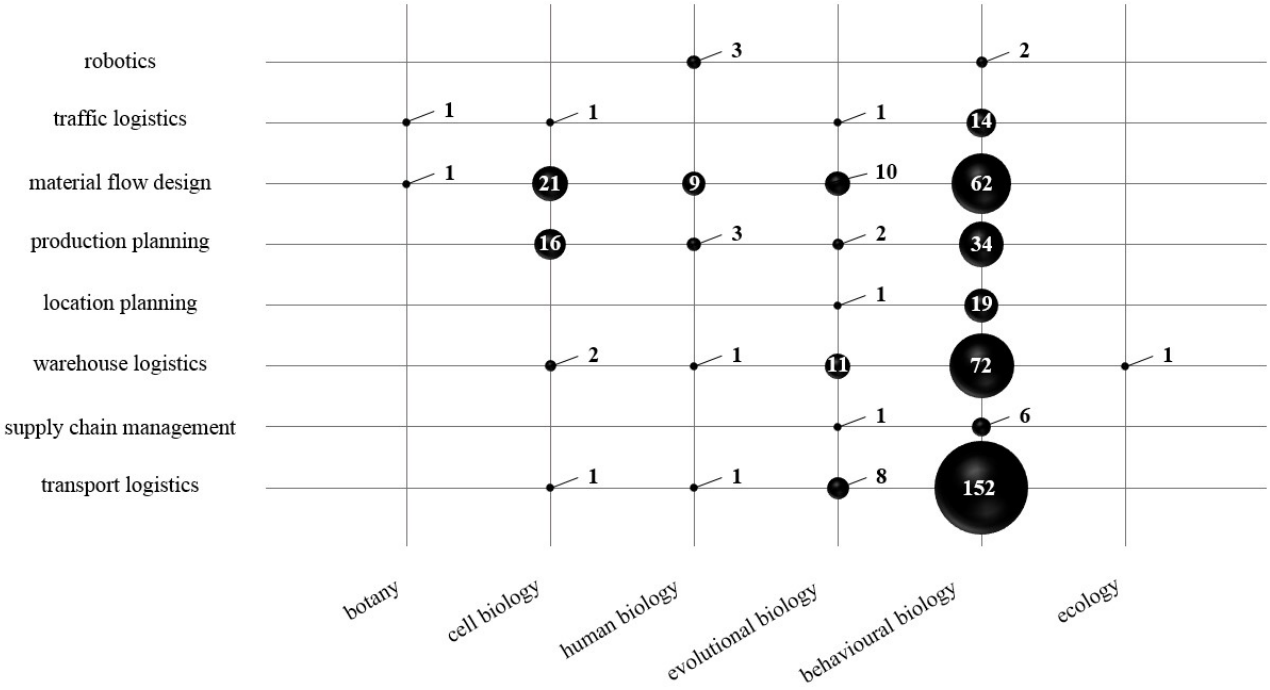

Figure 6. Overlapping subject areas in publications

But what is the particular content of these inter-connected research topics? To address this question we selected eight different intersection points or intersection couples, which will be briefly outlined. **(1)** Evolutional and Behavioural biology / transport and warehouse logistics – as shown above (in the discussion of Appendix 2) the main topic in this section is the Traveling Salesman Problem. Faster algorithms are developed to find acceptable, but still suboptimal solutions. Bionics is applied here, e.g. the behaviour of ants and bees have inspired different approaches of algorithms, but also the evolution of living beings provides help. Based on these algorithms, faster routes can be calculated, which are close to the optimum [18, 19, 21, 22]. **(2)** Cell, human and behavioural biology / material flow design and production planning. There are biomimetic solutions for planning of production orders and the organizational behaviour of individual departments, but also when configuring charging and discharging cycles.

Current topics within material flow design are, for example, driverless transport systems, layout of manufacturing cells or self-controlling material flows. Here, bionics tries to offer biologically inspired solutions, which are derived from the structure or the function of the cell, the swarm behaviour of various animals or the organization of the human nervous system respectively [16, 17, 23, 24]. **(3)** Behavioural biology / location planning and Supply Chain Management. Finding the right location for a distribution warehouse or the ideal location of supplier and customer network is a multiple task, and future changes e.g., customer growth must also be considered. In this case, the swarm behaviour of different animals provides ideas for biomimetic solutions. Current research tries to build up ideal networks with the ability to react quickly to customer needs and other demands [25-28]. **(4)** Behavioural biology / traffic logistics. Occurring problems with the infrastructure (e.g., traffic congestion, restrictions) is the content at off-site transport logistics. Current research efforts focus on solving this problem with biologically inspired algorithms. Above all, the behaviour of small animals (including ants, glowfly etc.) is used [20, 29]. **(5)** human and behavioural biology / robotics. According to our analysis, robotics is only a border area of bionics & logistics, but according to the study of Lepora et al. (2013), the most frequent topic in biomimetics. Nevertheless, it is impossible to imagine logistics without robots. Scientists attempt to abstract the human perception, so that robots can react in certain areas independently [30, 31].

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4 CONCLUSION

Biomimetics and logistics have been discussed broadly in the scientific literature regarding their particular discipline. We therefore conducted a bibliometric analysis to explore the amount and structure of the scientific research on the interdisciplinary topic of biomimetics applied to logistics. Additionally, our bibliometric analysis focused on identifying scientific journals and conferences with the greatest amount of publications and the most influential academic papers. When analysing the publications on the inter-connected topics bionics & logistics, it can be observed that biomimetics has expanded into many logistical fields in recent years. Principles of behavioural biology, in particular, are applied to various logistic research topics to which transport logistics contributes the largest share. Nevertheless, some topics (e.g. biological inspired factory layouts) have not been explored yet.

Between 2003 and 2013 the amount of publications (absolute figures) rose from 7 to 57, while citations per year rose from 6 to 93 in the same time period. Furthermore, as the trend analysis (compare 3.4) of the publication has shown, a trend towards finding biologically inspired solutions in the context of logistics is definitely recognizable. It was pointed out that the combined topic bionics & logistics grows significantly stronger than the respective disciplines. The leading country in terms of publication quantity is China, followed by Germany and the USA.

This study is based on contributions which are listed in WOS and Scopus databases. But it should be mentioned that this does not signify completeness. In Germany, for instance, the BIOKON Network carries out extensive activities in science and industry with regard to biomimetics. Although this fact has resulted in plenty of publications in German, most of them are not listed in WOS and Scopus. In other countries it could be similar, so that our study to some extent still remains ambiguous.

Another point of criticism arises in relation to the query couples. Even though we searched using numerous terms constructed from two words (one of bionical and one of logistical origin), we could have found a higher number of publications by expanding the query couple list with additional, perhaps even more appropriate matching search terms.

5 FUNDING

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LITERATURE

[1] Seebacher G, Winkler H. A Citation Anaylysis of the Research on Manufacturing and Supply Chain Flexibility. International Journal of Production Research, 2013, 51 3415-3427.

[2] Wiendahl H P, ElMaraghy H A, Nyhuis P, Zäh M F, Wiendahl H H, Duffie N, Brieke M. Changeable Manufacturing - Classification, Design and Operation. CIRP Annals - Manufacturing Technology, 2007, 783-809.

[3] Von Gleich A, Pade C, Petschow U, Pissarskoi E. Potentials and Trends in Biomimetics. Springer Heidelberg Dordrecht, London New York, 2010.

[4] Barthlott W, Neinhuis C. Purity of the sacred lotus or escape from contamination in biological surfaces. Planta, 1997, 1, 1-8.

[5] Tinello D, Winkler H. Bionik in der Logistik- Träumerei oder umsetzbares Potential? Proceedings of Logistics Systems Engineering. Munich, Germany, 2013, 19-31.

[6] Dorigo M, Di Caro G, Stützle T. Special issue on "Ant Algorithms". Future Generation Computer Systems, 2000, 16.

[7] Norton M J. Introductory Concepts in Information Science. Information Today, Inc. New Jersey: Information, 2001.

[8] Okubo Y, Bibliometric Indicators and Analysis of Research Systems: Methods and Examples. OECD Science, Technology and Industry Working Papers, 1997, [2014-07-06], http://dx.doi.org/10.1787/208277770603: OECD Publishing.

[9] Gebeshuber I C, Gruber P, Drack M. A gaze into the crystal ball: Biomimetics in the year 2059. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2009, 2899-2918.

[10] Lepora N F, Verschure P, and Prescott T J. The state of the art in biomimetics. BIOINSPIRATION & BIOMIMETICS, 2013, 8, Article number 013001.

[11] Bar-Ilan J. Which h-index? - A comparison of WoS, Scopus and Google Scholar. Scientometrics, 2008, 74, 257-271.

[12] Ball R, Tunger D. Science Indicators Revisited – Science Citation Index versus SCOPUS: A Bibliometric Comparison of Both Citation Databases. Information Services & Use, 2006, 26, 293-301.

[13] Merton R. The matthew effect in science. Science, 1968, 159, 56-62.

[14] Solimanpur M, Vrat P, Shankar R. An ant algorithm for the single row layout problem in flexible manufacturing systems. Computers and Operations Research, 2005, 32, 583-598.

[15] McKendall A R, Shang J. Hybrid ant systems for the dynamic facility layout problem. Computers and Operations Research, 2006, 33, 790-803.

[16] Tharumarajah A, Wells A J, Nemes L. Comparison of the bionic, fractal and holonic manufacturing system concepts. International Journal of Computer Integrated Manufacturing, 1996, 9, 217-226.

[17] Tharumarajah A, Wells A, Nemes L. Comparison of emerging manufacturing concepts. Proceedings of the 1998 IEEE International Conference on Systems, Man and Cybernetics, San Diego, California, USA, 1998, 325-331.

[18] Chen C H,Ting C J. An improved ant colony system algorithm for the vehicle routing problem. Journal of the Chinese Institute of Industrial Engineers, 2006, 23, 115-126.

[19] Fuellerer G, Doerner K F, Hartl R F, Iori M. Ant colony optimization for the two-dimensional loading vehicle routing problem. Computers and Operations Research, 2009, 36, 655-673.

[20] Lammer S, Helbing D. Self-control of traffic lights and vehicle flows in urban road networks. Journal of Statistical Mechanics-Theory and Experiment, 2008, Issue 4, Article number P04019.

[21] Hu K Y, Chang T S. An innovative automated storage and retrieval system for B2C e-commerce logistics. International Journal of Advanced Manufacturing Technology, 2010, 48, 297-305.

[22] Tang H Y, Li M J. An Improved Ant Colony Algorithm for Order Picking Optimization Problem in Automated Warehouse. In: Fuzzy Information and Engineering, Volume 2, Springer, Berlin-Heidelberg, 2009.

[23] Ryu K, Jung M. Agent-based fractal architecture and modelling for developing distributed manufacturing systems. International Journal of Production Research, 2003, 41, 4233-4255.

[24] Tang L, Cheng D. Study of logistic scheduling algorithm based on ant colonies optimization. Jisuanji Gongcheng/Computer Engineering, 2006, 32, 177-177+194.

[25] Chen Z, Wang Y. Research on Distribution Centers Location Problem. 2008 International Conference on Multimedia and Information Technology, Three Gorges, China, 2008, 438-441

[26] Shih C Y, Huang S. The study of distribution center location selection based on MAX-MIN ant algorithm. Journal of Quality, 2010, 17, 89-97.

[27] Wang K J, Chen M J. Cooperative capacity planning and resource allocation by mutual outsourcing using ant algorithm in a decentralized supply chain. Expert Systems with Applications, 2009, 36, 2831-2842.

[28] Wang H S. A two-phase ant colony algorithm for multi-echelon defective supply chain network design. European Journal of Operational Research, 2009, 192, 243-252.

[29] Teodorovic D A. Transport modeling by multi-agent systems: A swarm intelligence approach. Transportation Planning and Technology, 2003, 26, 289-312.

[30] Choi S H, Zhu W K. A bio-inspired intelligent approach to motion planning for mobile robots. Computer-Aided Design and Applications, 2011, 8, 773-783.

DOI: 10.2195/lj_Rev_tinello_en_201701_01
URN: urn:nbn:de:0009-14-44919

[31] Fernandez J D, Albiez J C, Kirchner F. Bio-inspired robotic handling of heterogeneous logistics goods. 2007 Ieee International Conference on Automation and Logistics, Jinan, China, 2007, 192-197.

[32] Gutenschwager K. Online-Dispositionsprobleme in der Lagerlogistik. Heidelberg, Physica-Verlag, 2002. – ISBN 3-7908-1493-8.

[33] Buchholz J, Clausen U. Handbuch der Verkehrslogistik. Berlin, Springer Verlag, 1998. – ISBN 3-540-64517-9.

[34] Neugebauer R. Handbuch – Ressourcenorientierte Produktion. München/Wien, Carl Hanser Verlag, 2014. – ISBN 978-3-446-43008-2.

[35] Fuller J L. Robotics. Prentice Hall, New York, 1998. – ISBN: 978-0130955432

[36] Domschke W, Krispin G. Location and layout planning. A survey. OR Spektrum, 19 1997: 181-194.

DOI: 10.2195/lj_Rev_tinello_en_201701_01
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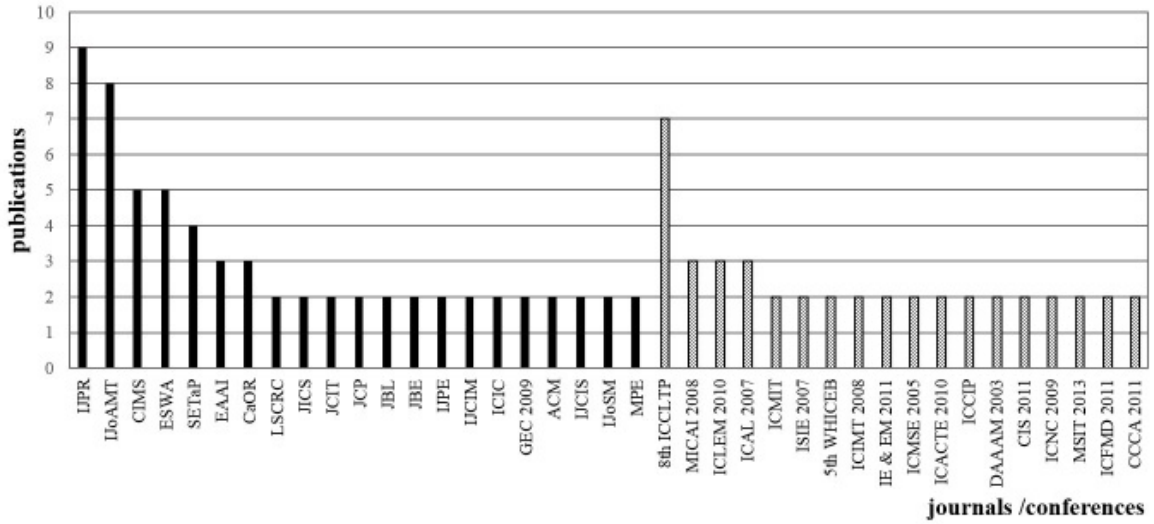
APPENDIX 1. AMOUNT OF PUBLICATIONS FROM 1990-2014 IN JOURNALS (LEFT) AND CONFERENCES (RIGHT)



APPENDIX 2. MOST FREQUENTLY CITED PUBLICATIONS

Frequency	Title	Author(s)	Year	Journal / Conference
36	An ant algorithm for the single row layout problem in flexible manufacturing systems	Solimanpur/ Vrat/ Shankar	2005	Computers and Operations Research
34	Comparison of the bionic, fractal and holonic manufacturing system concepts	Tharumarajah/ Wells/ Nemes	1996	International Journal of Computer Integrated Manufacturing
23	An improved ant colony system algorithm for the vehicle routing problem	Chen/ Ting	2006	Journal of the Chinese Institute of Industrial Engineers
23	Hybrid ant systems for the dynamic facility layout problem	McKendall Jr./ Shang	2004	Computers and Operations Research
12	Self-control of traffic lights and vehicle flows in urban road networks	Lammer/Helbing	2008	Journal of Statistical Mechanics-Theory and Experiment
11	Ant colony optimization for the two-dimensional loading vehicle routing problem	Fuellerer/Doerner/Hartl/Iori	2009	Computers and Operations Research
10	Ant colony optimisation for machine layout problems	Corry/Kozan	2004	Computational Optimization and Applications
9	Comparison of emerging manufacturing concepts	Tharumarajah/ Wells/Nemes	1998	Proceedings of the 1998 IEEE International Conference on Systems, Man, and Cybernetics.
9	Soft computing optimization methods applied to logistic processes	Silva/Sousa/ Runkler/Palm	2005	International Journal of Approximate Reasoning
9	Self-organization in distributed manufacturing control: State-of-the-art and future trends	Bousbia/ Trentesaux	2002	2002 IEEE International Conference on Systems, Man and Cybernetics

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8	A hybrid intelligent algorithm for the vehicle routing with time windows	Zhang Q.W./ Zhen/ Zhu/ Zhang W.S./ Ma	2008	Advanced Intelligent Computing Theories and Applications, Proceedings
8	Agent-based fractal architecture and modelling for developing distributed manufacturing systems	Ryu/ Jung	2003	International Journal of Production Research
7	Honey Bees Mating Optimization algorithm for large scale vehicle routing problems	Marinakis/ Marinaki/ Dounias	2010	Natural Computing
6	Rescheduling and optimization of logistic processes using GA and ACO	Silva/ Sousa/ Runkler	2008	Engineering Applications of Artificial Intelligence
6	An enhanced ant colony optimization (EACO) applied to capacitated vehicle routing problem	Lee C.Y./ Lee Z.J./ Lin/ Ying	2010	Applied Intelligence
5	Optimization of logistic processes in supply-chains using meta-heuristics	Silva/ Runkler/ Sousa/ da Costa	2003	Progress in Artificial Intelligence
5	A hybrid particle swarm optimization algorithm for the vehicle routing problem	Marinakis/ Marinaki/ Dounias	2010	Engineering Applications of Artificial Intelligence
5	A new saving-based ant algorithm for the Vehicle Routing Problem with Simultaneous Pickup and Delivery	Catay	2010	Expert Systems with Applications
4	Route selection for emergency logistics management: A bio-inspired algorithm	Zhang X.G./ Zhang Z.L./ Zhang Y.J./ Wei/ Deng	2013	Safety Science
4	Contract-Net based scheduling for holonic manufacturing systems	Kanchanasevee/ Biswas/ Kawamura/ Tamura	1997	Architectures, Networks, and Intelligent Systems for Manufacturing Integration
4	Partner selection of agile supply chain based on ant colony optimization algorithm	Jiang/ Xia/ Zhang/ Yin	2006	Xitong Fangzhen Xuebao / Journal of System Simulation
4	A hybrid 'bee(s) algorithm' for solving container loading problems	Dereli/ Das	2011	Applied Soft Computing
4	Improved ant colony algorithm for the VRPSPD with maximum distance constraint	Zhang/ Tian/ Zhang/ Liu	2008	Xitong Gongcheng Lilun yu Shijian/System Engineering Theory and Practice
4	Bio-inspired and pheromone-based shop-floor control	Scholz-Reiter/ De Beer/ Freitag/ Jagalski	2008	International Journal of Computer Integrated Manufacturing
4	A holonic self-organization approach to the design of emergent e-logistics infrastructures	Ulieru/ Unland	2004	Engineering Self-Organising Systems: Nature-Inspired Approaches to Software Engineering
4	A block transportation scheduling system considering a minimisation of travel distance without loading of an interference between multiple transporters	Myung/ Ju-Hwan	2011	International Journal of Production Research

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3	Information and material flows in complex networks	Helbing/ Armbruster/ Mikhallov/ Lefeber	2006	Physica a-Statistical Mechanics and Its Applications
3	Automation of robotic assembly processes on the basis of an architecture of human cognition	Mayer/ Schlick/ Ewert/ Behnen/ Kuz/ Odenthal/ Kausch	2011	Production Engineering
3	Vehicle routing problem with time reservation under B2C electronic commerce and ant colony algorithm for multi-objective optimization	Li/ Liu/ Tang	2011	Kongzhi Lilun Yu Yingyong/Control Theory and Applications
3	A combinatorial Artificial Bee Colony algorithm for traveling salesman problem	Karaboga/ Gorkemli	2011	2011 International Symposium on INnovations in Intelligent SysTems and Applications, INISTA 2011
3	Optimization of logistic systems using fuzzy weighted aggregation	Silva/ Sousa/ Runkler	2007	Fuzzy Sets and Systems
3	Development of a decision support system for solving container loading problems	Dereli/ Das	2010	Transport
3	A two-phase ant colony algorithm for multi-echelon defective supply chain network design	Wang	2009	European Journal of Operational Research
3	A self-organising view of manufacturing enterprises	Tharumarajah	2003	Computers in Industry
3	The application of improved ant colony algorithm for emergency logistics vehicle routing problem	Ma/ Qi/ Diao	2011	International Journal of Advancements in Computing Technology
3	A genetic ant colony optimization approach for concave cost transportation problems	Altiparmak/ Karaoglan	2007	2007 Ieee Congress on Evolutionary Computation, Vols 1-10, Proceedings
3	Order picking problem based on ant colony algorithm	Chenqi Q./ Meijuan/ Xuebo	2009	Xitong Gongcheng Lilun yu Shijian/System Engineering Theory and Practice
2	Improved ant colony algorithm for logistics distribution routing problem	Yue/Zhou/Yue/ Sun	2006	CIMS
2	A PSO-based ant colony optimization for VRPTW	Wu/Li/Chen/Hu	2008	8th International Conference of Chinese Logistics and Transportation Professionals
2	Cooperative capacity planning and resource allocation by mutual outsourcing using ant algorithm in a decentralized supply chain	Wang/Chen	2009	Expert Systems with Applications
2	A Hybrid Algorithm Based on ACO and PSO for Capacitated Vehicle Routing Problems	Kao/Chen/Huang	2012	Mathematical Problems in Engineering
2	Design, modeling and stability control for an actuated dynamic walking planar bipedal robot	Chen/Shih/Shih/ Wang	2013	Journal of Vibration and Control

2	A concept for bionic manufacturing systems based on DNA-type information	Ueda K.	1992	Ifip Transactions B-Applications in Technology
2	An ant colony system approach for fuzzy traveling salesman problem with time windows	Sarhadi/Ghoseiri	2010	International Journal of Advanced Manufacturing Technology
2	Swarm intelligence: application of the ant colony optimization algorithm to logistics-oriented vehicle routing problems	Bell/Griffis	2010	Journal of Business Logistics
2	Path planning based on the swarm intelligence algorithm	Li/Chen/Zhang	2007	Qinghua Daxue Xuebao/Journal of Tsinghua University
2	Receding-horizon decision-making of supply chain based on ant colony optimization algorithm	Yang/He	2010	CIMS
2	Multi-supplier selection problem solution based on improved ant colony algorithm	Dong/Wang/Lv/Gao	2007	CIMS
2	Minimisation of supply chain cost with embedded risk using computational intelligence approaches	Kumar/Tiwari/Babiceanu	2010	International Journal of Production Research
2	Optimizing logistic distribution routing problem based on improved ant colony algorithm	Zhang/Lin/Wu/Tong/Dong	2008	Zhejiang Daxue Xuebao (Gongxue Ban)/Journal of Zhejiang University (Engineering Science)
2	The application of the improved hybrid ant colony algorithm in vehicle routing optimization problem	Zhang/Zhou	2010	ICFCC 2010
2	Logistics distribution center allocation based on ant colony optimization	Qin	2006	Xitong Gongcheng Lilun yu Shijian/System Engineering Theory and Practice
2	Transport modeling by multi-agent systems: A swarm intelligence approach	Teodorovic D. A.	2003	Transportation Planning and Technology
2	Improved Ant Colony Algorithm for Vehicle Scheduling Problems of Military Logistics Distribution	Gong/Huang/Yang/Shi/Li/Iee e	2010	Proceedings of 2010 International Conference on Logistics Systems and Intelligent Management, Vols 1-3
2	Improved ant colony algorithm and application for vehicle routing problem	Zhang J./Zhang Z.	2011	ITAIC 2011
2	Research on Order Picking Optimization Problem of Automated Warehouse	Chang/ Liu/ Xin	2007	Systems Engineering - Theory & Practice
2	Task Scheduling of Agv in Fms Using Non-Traditional Optimization Techniques	Udhayakumar/Kumanan	2010	International Journal of Simulation Modelling
2	A genetic algorithm with the heuristic procedure to solve the multiline layout problem	Sadrzadeh	2012	Computers & Industrial Engineering

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1	The logistics vehicle routing optimization method and implementation based on ant colony algorithm	Chen/Xie/Fan/Li/Zhang/Huang	2012	Journal of Computational Information Systems
1	Investigating the performance of bees algorithm in solving quadratic assignment problems	Fon/Wong	2010	International Journal of Operational Research
1	Using bees algorithm for material handling equipment planning in manufacturing systems	Sayarshad	2009	The International Journal of Advanced Manufacturing Technology
1	Development of a simulation-based optimisation for controlling operation allocation and material handling equipment selection in FMS	Mahdavi/ Shirazi/ Sahebjamnia	2011	International Journal of Production Research
1	Solving a time constrained two-crane routing problem for material handling with an ant colony optimisation approach: an application in the roof-tile industry	Hirsch/ Palfi/ Gronalt	2012	International Journal of Production Research
1	Integrated scheduling of flexible manufacturing system using evolutionary algorithms	Udhayakumar/ Kumanan	2011	The International Journal of Advanced Manufacturing Technology

APPENDIX 3. CATEGORIES WITHIN LOGISTICS [32-36]

Transport logistics deals with the external, physical disposal of goods within a logistics network. Loading and unloading operations also belong to this area.

Within **material flow design,** the linkage of all processes is determined containing the extraction, treatment, storage and distribution of goods within defined areas (working systems).

Location planning aims to determine optimal location for a facility. An efficient throughput from the supplier to the customer is the basic intention underlying the plan.

Supply Chain management (SCM) deals with the coordination of the overall flow (material-, information- and financial flow) from the supplier up to the final consumer.

Production planning and production control deals with all parameters and resources which are necessary for the planning and realisation of all production and manufacturing activities.

Traffic logistics is similar to transport logistics with external transports, but hereby the selected infrastructure of the different transport carriers is included.

Warehouse logistics concentrates on the storage and management of goods in a warehouse. This includes not only the transport of goods in the warehouse, but also all movements from storage to retrieval.

Robotics deals with automated moving devices consisting of several movable axes, which allow to manipulate objects in their surroundings.