

A Comparative Bibliometric Analysis of Taguchi-Centered Optimization in Plastic Injection Moulding

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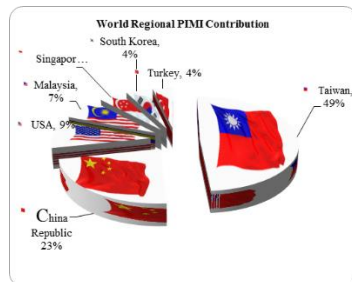
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Graphical abstract



Abstract

Plastic injection molding is one of the most common methods of part manufacturing. Different optimization techniques are commonly used in this industry to satisfy for the multi-input multi-output (MIMO) characteristics of the injection process. The primary objective of this study is to provide a comparative Bibliometric analysis on injection molding process optimization during the previous decade based on the top seven methodologies found in the literature. Triple criteria of chronological trend, geographical dispersion and academic reputation are used for evaluating the overall performance of each method as well as each hybrid set. The survey will also include two complementary analyses for the Taguchi based methods. Firstly, a signal to noise ratio (SNR) analysis, followed by a secondary analysis of the average number of control and response factors as well as the orthogonal array levels used in the experimental design will be conducted. The results of the study reveal that Taguchi Method (TM), GA and RSM are the three most popular optimization techniques used in plastic injection molding worldwide. TM is also proved to be a better optimization tool when combined with other heuristic methods such as ANN and GA, especially in the field of product and mould design. For processing parameters, Taguchi still remains to be the core optimization technique.

Keywords: Optimization; plastic injection; DOE; SNR; bibliometrics

Abstrak

Pengacuan suntikan plastik adalah salah satu kaedah yang paling biasa digunakan dalam pembuatan komponen. Teknik pengoptimuman yang berbeza biasanya digunakan dalam industri untuk memenuhi keperluan input berbilang output berbilang (MIMO) dalam proses suntikan plastik. Objektif utama kajian ini adalah untuk menyediakan satu analisis bibliometrik bagi pengoptimuman proses pengacuan suntikan dalam tempoh sedekad sebelum ini menggunakan tujuh kaedah paling popular berdasarkan kajian terdahulu. Tiga kriteria iaitu aliran kronologi, penyebaran geografi dan reputasi akademik digunakan untuk menilai prestasi keseluruhan setiap kaedah serta setiap set hibrid. Kaji selidik ini juga akan merangkumi dua analisis pelengkap kepada kaedah berasaskan Taguchi. Analisis nisbah isyarat-hingar (SNR) diikuti oleh analisis purata bilangan faktor kawalan dan sambutan serta tahap pelbagai ortogonal digunakan dalam reka bentuk eksperimen. Kebaikan dan juga keburukan kaedah TM juga akan ditonjolkan berbanding dengan teknik pengoptimuman lain yang berdasarkan tiga kriteria tadi. Keputusan kajian menunjukkan bahawa kaedah TM, GA dan RSM adalah tiga kaedah pengoptimuman paling popular yang digunakan dalam proses pengacuan suntikan plastik di seluruh dunia. Kaedah Taguchi (TM) juga terbukti menjadi kaedah pengoptimuman yang lebih baik bila digabungkan dengan kaedah heuristik lain seperti ANN dan GA, terutamanya dalam reka bentuk produk dan acuan manakala untuk pemprosesan parameter, Taguchi masih kekal sebagai teknik pengoptimuman yang paling dominan.

Kata kunci: Pengoptimuman; suntikan plastik; DOE; SNR; bibliometrik

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1.0 INTRODUCTION

Plastic injection moulding is recognized as a technique that is widely used to produce a variety of plastic parts covering a wide range of applications such as household, medical, automotive,

etc. The manufacturing process of these plastic parts is involved with several parameters that may directly or indirectly affect the quality of the final product. Therefore, the injection moulding is usually classified as a MIMO process in which multiple factors may influence the injection process and on the other hand, the

product quality is also a function of multiple characteristics that need to be met simultaneously so that the product is regarded as a standard quality product for being marketed.

Six criteria of material, man (operator), part design, mold design, machine parameters and processing parameters are found as the major causes of most of the quality defects in plastic injection moulding [1, 2]. Once the main source of defects is identified, different techniques may be applied to optimize the product quality. Different techniques of Designs of experiment (DOE) such as factorial design (FD), response surface methodology (RSM) and Taguchi method have routinely been used as an optimizing tool in the injection moulding. Besides the so-called DOE-based methods, the appearance of heuristic and meta-heuristic approaches such as genetic algorithm (GA) and artificial neural network (ANN) has offered new solutions for the common injection moulding optimization issues [2].

Taguchi method (TM) is introduced in this paper as a core methodology that is widely used in plastic injection molding, either individually or in combination with other DOE and/or soft computing techniques such as ANN, GA and fuzzy logic among others. Different optimization methods are then compared based on pre-determined **triple criteria** of **chronological trend**, **geographical dispersion** and **academic reputation**. A complimentary analysis is also provided for the DOE-based methods focusing of SNR, control and response factors as well as the levels of orthogonal arrays used for the experimental design. The primary goal of this study is to provide a Bibliometric analysis of the top seven methodologies found in the literature during previous decade. Unlike a review paper, the focus of this paper is to highlight some underlying facts that have been less paid attention in the field of PIM research background.

The results in this paper have been statistically derived from the holistic analysis of 133 unique papers extracted from journal citation reports (JSR) of Thomson Reuters web of science database from 2001 to March 2013, using **citation analysis** as one of the most common Bibliometric methods. By referring to Taguchi method as a core methodology, the findings of this Bibliometric study reveal some underlying aspects as well as suggesting practical implications for selecting the best and most compatible optimization strategy in the field of plastic injection moulding based on the proposed triple criteria.

2.0 A REVIEW OF TAGUCHI METHOD

Taguchi method is technically classified as one of a group of optimization techniques commonly known as the umbrella term, design of experiments (DOE). It was originally pioneered in 1948 by Japanese statistician and Deming prize winner; Dr. Genichi Taguchi to improve quality through Robust Design of products and production processes. The method was primarily based on traditional concepts of DOE such as full and fractional factorial design and orthogonal arrays but later in the 1980s and parallel to its introduction in the United States, new features such as signal-to-noise ratios (SNR) and tolerance design were also added to the traditional techniques [3].

Taguchi method is considered as a technique that has gained much of its credit from statistical analysis of robust design. The main objective of this method is to achieve economical quality design based on a very limited number of experimental runs. This salient feature is most applicable in cases where quality is a multi-variable function such as in plastic injection molding [3, 4]. Therefore in plastic injection molding industry (PIMI), the number of experimental runs needs to be reduced to a minimum possible level to save for the quality-related time and costs [5]. In this regard, Taguchi's DOE employs the Taguchi loss function

(TLF) to investigate both product parameters and key environmental factors by setting variation reduction as the primary goal of quality improvement.

2.1 Taguchi Loss Function (TLF)

Taguchi loss function (TLF) is strongly focused on minimizing losses or cost. Such quality philosophy is named as an "enlightened approach" by W. H. Moore which is based on the following triple assumptions: (a) - in TLF, the smallest loss is obtained by the target value for each product quality characteristics (b) - total loss increases with an increase in process variation and finally (c) - loss should be measured in monetary units [6].

As it is illustrated in Figure 1 on the right, TLF states a nonlinear relationship for loss fluctuation as being deviated from the target value, which is in contrast with the traditional view of zero point loss for the interval between lower specification limit (LSL) and upper specification limit (USL).

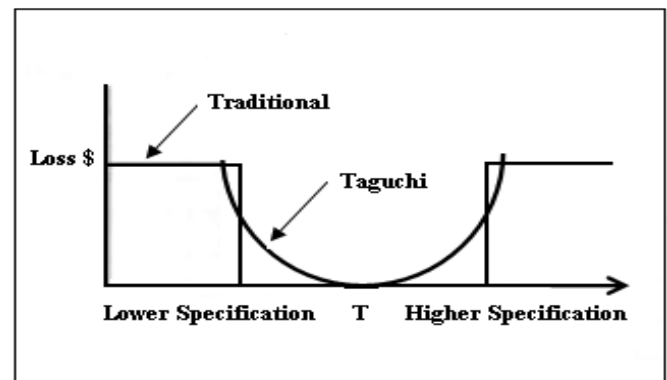


Figure 1 Taguchi loss function vs. traditional loss function [6]

The TLF shown above can be mathematically modeled as a simple quadratic equation that compares the measured value of a unit of output X to the target T as given by Equation (1) in which $L(X)$ is the expected loss associated with any value of X variable representing an specific quality characteristic:

$$L(X) = (X - T)^2 \quad (1)$$

Equation (1) can be operated to set quality performance measures that allow for the optimization of any product's quality characteristic. For any quality characteristic, as a response variable, it is important to know both values of its average and variation.

2.2 Signal-to-Noise Ratio (SNR)

Equation (1) suggests that the values of average and variation for any response variable can be combined as a single measure known as "signal-to-noise ratio (SNR)". Taguchi method is then used to select the appropriate levels of design parameters that will maximize the relevant SNR ratio to be used as a criterion to reduce the amount of variation for product's quality characteristics.

SNR (α) is generally calculated based on the following three concepts: 1. *NOB* (nominal-the-best), 2. *LIB* (Lower-is-better), 3. *HIB* (Higher-is-better). *NOB* type of problem attempts to minimize mean square error (MSE) around a specific target value and is calculated by Equation (2) in which μ and σ is the mean and standard of the response variable deviation respectively.

$$\text{SNR} (\alpha_{\text{NOB}}) = -10 \log_{10} (\mu^2/\sigma^2) \quad (2)$$

LIB is calculated by Equation (3), with “i” ranging from 1 to “n” and X is the value of the measured variable. This type of S/N ratio is used where the objective is solely to minimize the value of a certain quality characteristic.

$$\text{SNR} (\alpha_{\text{LIB}}) = -10 \log_{10} (1/n \sum X_{i2}) \quad (3)$$

And finally HIB type of SNR is used when the intention is to maximize the selected quality characteristic and is calculate by Equation (4) in which “n” is the number of replication and “i” ranges from 1 to “n” [2].

$$\text{SNR} (\alpha_{\text{HIB}}) = -10 \log_{10} (1/n \sum 1/X_{i2}) \quad (4)$$

3.0 BIBLIOMETRIC METHODOLOGY

One common way of conducting Bibliometric research is to use the *Social Science Citation Index*, the *Science Citation Index* or the *Arts and Humanities Citation Index* to trace citations [18]. Therefore, The Bibliometric analysis in this section is based on the search findings extracted from *Journal Citation Reports*®, *Sciences Citation Index*® accessed via accessed via Web of Science™, during a period covering the last decade from the year 2001 to March 2013.

The analysis is conducted through a consecutive three-step process. Firstly, a preliminary desktop search is done to find a list of all possible alternatives that have been reported as an optimizing tool in the selected literature. The methods are then investigated with respect to their relative popularity in plastic injection moulding industry (PIMI). In this phase, the result of the desktop search is shortlisted by adopting a basic data-mining approach that sets “optimization” and “plastic injection moulding” as two fixed keywords and alternatively changing the respective optimizing method such as ANN, GA, RSM, etc., to update the search findings.

The recursive process is continued for each of the 13 alternatives to come up with the final list of seven most popular methodologies. And finally, in the third phase all the gathered data is coomplied for a comprehensive statistical analysis based a triple criteria framework that follows in the next section.

4.0 RESULTS AND DISCUSSION

In the following four sub-sections (4.1- 4.4), the results of the triple criteria and the MIMO analysis will be graphically elaborated. It is worth emphasizing that the following results have been statistically derived from the holistic analysis of papers published in journal citation reports (JSR), Thomson Reuter’s database and are independent of the shape as well as the material used in the injection moulding process.

4.1 Chronological Trend Analysis

Monitoring the chronological trend of any phenomenon can provide a reasonable proof of its sustainability and reliability based on the observed fluctuations. Therefore, major research articles covering a total number of 133 unique papers were investigated in this study referring to their chronological trend and the results are graphically illustrated in this section.

Figure 2, on the next page shows a graphical illustration on how the relevant data for each of the seven selected methodologies were collected from the web of science database.

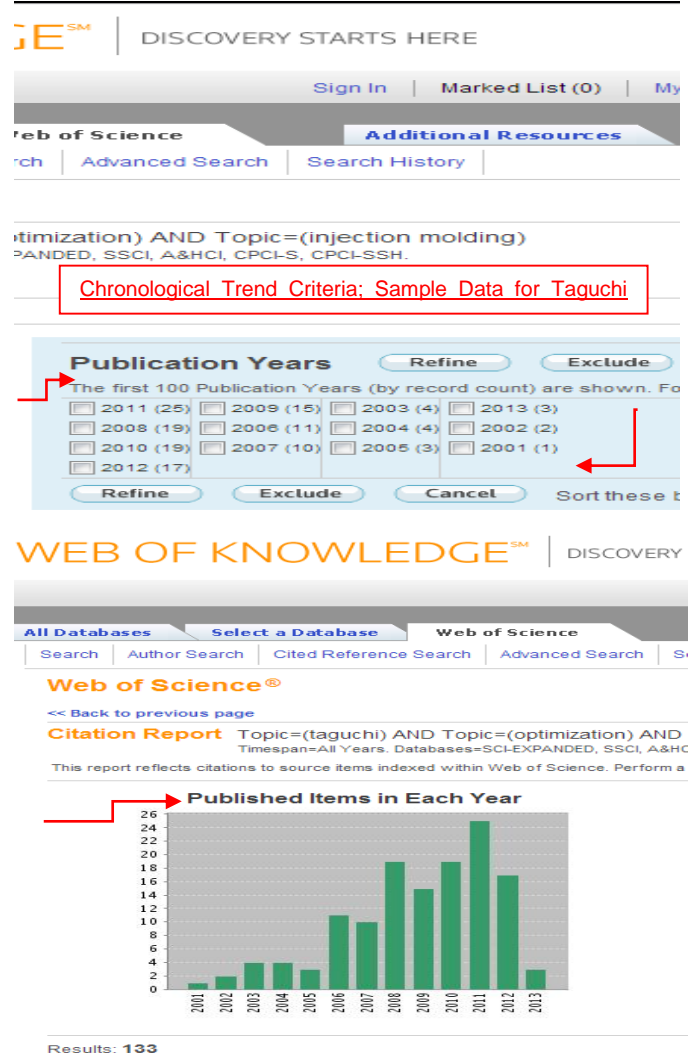


Figure 2 Chronological trend data source [17]

After compiling all data related to each of the seven selected methodologies, the results are combined for each year individually. The overall chronological trend is then reported in Figure 3 by referring to the number of ISI papers published each year in the field of PIM. The respective “Two Period Moving Average” trend line is also provided.

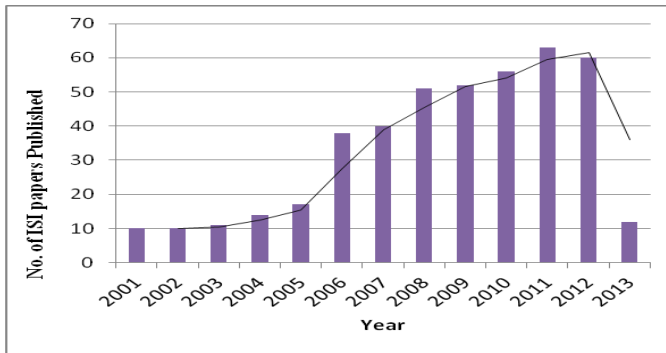


Figure 3 Chronological trend of research in PIMI based ISI papers [17]

The histogram in Figure 3 shows that in general, the interest for research in injection moulding optimization has almost steadily increased, ignoring the minor fluctuations during 2007-2010. Maximum contribution also goes to the year 2011 with a total number of 61 published papers.

Unlike Figure 3 which has no bias on the type of optimizing tool, in Figure 4 below, the seven methodologies are compared based on their respective contribution on a scale ranging from 0-100.

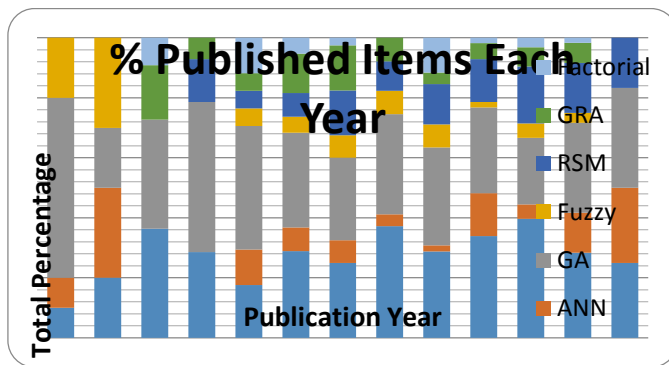


Figure 4 Annual percentile comparison of methodology contribution in PIMI [17]

From Figure 4, it can be inferred that, GA (in green) and Taguchi method (in blue) are used as core methodologies in most of the optimization problems in plastic injection molding and therefore the term *Taguchi-centered Optimization* is a well describing terminology for hybrid optimization techniques in PIM that are dependent upon Taguchi as the core optimization tool.

On the other hand, the *Paereto chart* in Figure 5 is derived by adding up the numerical equivalent of data in Figure 4 for each single method during the whole period. The result proves that compared to other methods, Taguchi, GA, RSM and ANN are the top four in a decreasing order of popularity with an overall of % 80 contribution based on the 80:20 or Pareto rule.

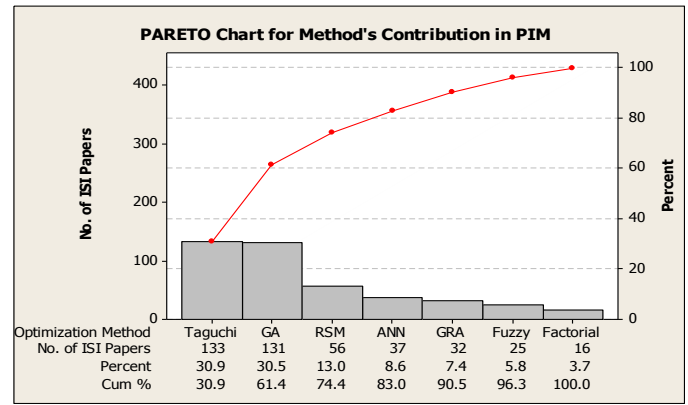


Figure 5 PARETO Chart for method contribution in PIM

4.2 Geographical Dispersion Analysis

In this section, different countries/territories are ranked with respect to their total contribution in the field of plastic injection moulding optimization. The sample procedure for collecting the relevant data for each methodology is depicted in Figure 6 below, extracted from science citation index database.

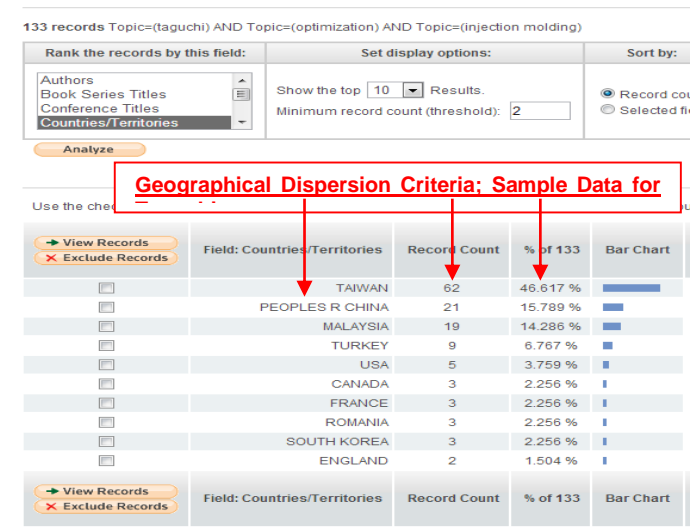


Figure 6 Geographical dispersion data source [17]

The pie chart in Figure 7 shows the respective percentile share of each of the top seven countries as the most popular research center in plastic injection molding worldwide

Based on the results, it can be seen that the research in this field is more concentrated in Asian countries with Taiwan and China Republic ranking as the first and second most popular. The USA ranks third with a meaningful difference with the top two countries while *Malaysia* is a close runner up for the USA. Singapore, South Korea and Turkey share the fifth place with the same degree of popularity of 4% for each individual country.

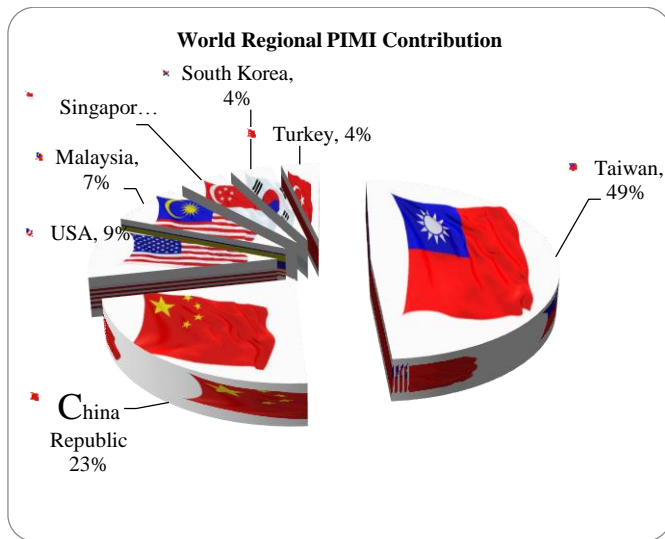


Figure 7 Worldwide geographical research concentration of PIMI [17]

4.3 Academic Reputation Analysis

As a rule of thumb, the most referred research papers and methodologies are the ones with a high level of impact factor. Therefore three sub-criteria of (1): total citation, (2): h-index (showing the popularity of the research work) and (3): average citation per item (ACPI) were extracted from JSR database and implemented in this section to compare the seven methods on their respective academic reputation in the plastic injection moulding industry. The three sub-criteria are marked with a red arrow in Figure 8 below.

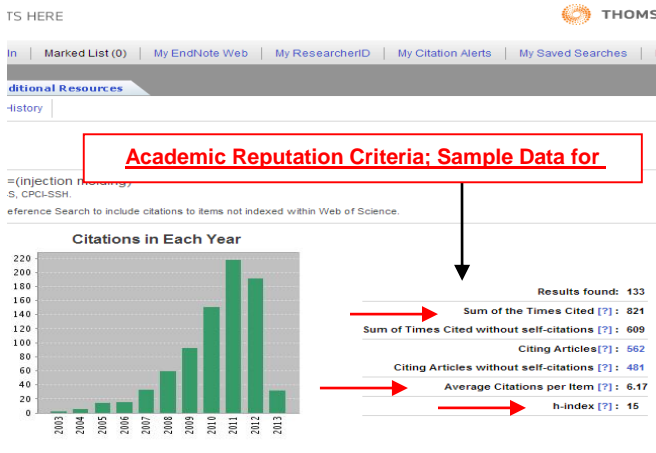


Figure 8 Academic reputation data source [17]

Based on the results in Figure 9, Taguchi and GA have obtained the highest total citation as compared to other five methods. It terms of h-index, it is also shown that GA and Taguchi have the highest rank which is expected and is in an indication of their absolute popularity as the optimal tools in plastic injection moulding industry. The minimum score on total citation goes for fuzzy and GRA. The minimum h-index also refers to Factorial Design (FD), though; it has obtained the maximum score on the average citation per item index. For ANN,

Fuzzy and GRA, “ACPI” and “h-index” values are reported to be almost coincident.

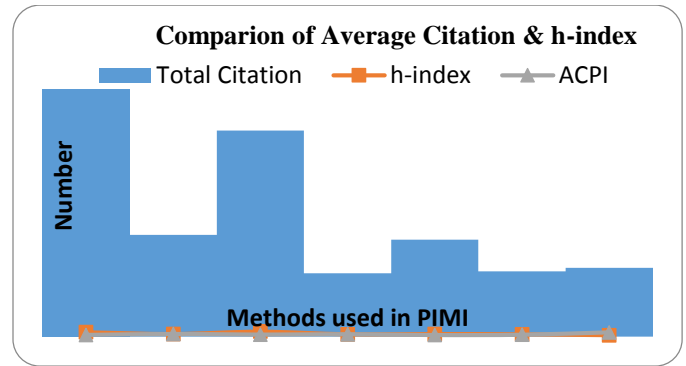


Figure 9 Academic reputation of 7 top methodologies in PIMI [17]

4.3 MIMO Taguchi-Based Analysis

In this section, a 3-layer DOE-centered framework is innovatively introduced for the first time to analyze ten selected papers in which Taguchi method was used as a core optimizing tool. The proposed framework includes three supportive layers as follows:

The first layer in Table 1 (key concept analysis) provides a summary of the objective, material & methods as well as the salient findings of the research. The second layer in Table 2 (MIMO fact sheet) is focused on major control and response factors that were used in the experimental design phase in plastic injection moulding optimization. And finally, the third layer in Table 3 (M2P2-SNR) illustrates a triple analysis on the scope, SNR and the orthogonal array characteristics used in the respective DOE methods. Each of the ten papers is represented in one row in Tables 1, 2, 3 with the same row number in all three tables.

Table 1 Layer I: key concept analysis

Z	Research Objective	Material Methods	Major Remarks
1	Prediction of mould low surface roughness	Al 7075-T6 FFD, RSM, ANN	Artificial neural Network is by 2.05 % to 1.48% difference in error more accurate than RSM [7]
2	Effect analysis of Nano-platelets dispersion degree	Metal mixed PP/clay Taguchi orthogonal array	Injection flow rate & back pressure as dominant factors Interaction between back pressure and screw rotation speed was significant [8]
3	Minimizing of wrappage Temperature difference	Hybrid Taguchi, FEM, ANN, abductive Design & simulated annealing	FEM-based simulation & simulated annealing-based optimization approach Applicable to parts with free-form geometry [9]
4	-Analysis of 3-D biodegradable polymeric	PLA 7000D	Providing a reference data for the processing window of biodegradable polymeric scaffold

4	scaffold on precision injection molding	FEM combined Taguchi	3-D numerical simulation for flow situation on precision injection molding of biodegradable polymeric [10]
5	Analysis of process parameters and cross-sectional dimensions on tensile strength	Polypropylene (PP) & high density polyethylene (HDPE)	- Melt temperature, mold temperature, injection speed, and packing pressure are the most influential factors
		Taguchi's orthogonal arrays	- Microinjection molding in not compatible e with the result of a standard test foe weld line strength [11]
6	effect of weld line of plastic parts appearance quality	Taguchi experimental design	-Weld line appearance is mostly influenced by melt temperature, injection velocity & injection pressure[12]
7	To restrain porosity creation and minimizing thickness reduction.	Hybrid neural network algorithm-3D Timon simulation and Taguchi	Eliminating the need for experiments by using a numerical simulation software named Timon-3D™ [12]
8	minimizing shrinkage and wrappage for PP and PS	polypropylene & polystyrene	-Use of Invasive Weed Optimization (IWO) algorithm in mathematical modeling
		Regression & ANOVA Analysis	-Reducing shrinkage up to 1 % as compared to previous studies [13]
9	An innovative search method for robust process parameters	PMMA	- Reducing the effect of environmental noise on part quality
		Taguchi orthogonal array	-Deficient rate of the new model is 0 to 21 per 100 items as compared to Taguchi [14]
10	Improve the drawbacks of the Taguchi method	PEEK	Based on actual experimental work and determination of optimum conditions using statistical tools [15]
		DOE, Orthogonal arrays, ANOVA	

Table 2 Layer II: MIMO fact sheet

No.	Critical Control Factors	Response(s)
1	feed, cutting speed, axial–radial depth of cut & machining tolerance	Mould surface roughness
2	screw rotational speed, back pressure, injection flow rate and holding pressure	storage modulus
3	Runner diameter ,Runner length ,Gate diameter Gate length, Material thickness	Warppage, temperature, time
4	Melt temperature ,mold temperature, injection pressure, packing time	deflection
5	mold temperature, packing pressure , melt temperature, injection speed, injection acceleration, packing time	tensile strength
6	melt temperature, injection velocity, and injection pressure	Weld line appearance

7	injection time, injection temperature, mold temperature and holding/cooling time	thickness reduction, volumetric distortion
8	melting temperature, packing pressure, packing time and injection pressure	shrinkage
9	Injection temperature , Back pressure, Mold temperature	replication
10	mold temperature, pre-elasticity, injection pressure, injection speed, screw speed, packing/cooling pressure/time	Screw outer diameter, tensile strength and twisting strength.

Table 3 Layer III: M2P2-SNR analysis

No.	M2P2 Analysis	S/N Ratio Analysis			DOE Analysis ^a			
	Material/Mould Product/Process	$\frac{N}{O}$ $\frac{B}{B}$	$\frac{L}{I}$ $\frac{B}{B}$	$\frac{H}{I}$ $\frac{B}{B}$	N_{CF}	N_{RV}	N_{LE}	N_{EX}
1	Mould design	1	0	0	5	1	3	243
2	Process parameter	0	1	0	4	1	2	16
3	Mould Design	1	0	0	5	3	3	243
4	Process parameter	0	1	0	4	1	3	81
5	Process parameter	1	0	0	6	1	2	64
6	Process parameter	0	1	0	3	1	3	27
7	Product design	0	1	0	4	2	3	81
8	Mold parameters	0	0	1	4	1	3	81
9	Process parameter	0	1	0	3	2	2	2 ³
10	Process parameter	0	1	0	7	3	2,3	2 ^{*7} ₃

^a N_{CF} refers to the number of control factors, N_{RV} is the number of response variables, N_{LE} is the orthogonal array level and N_{EX} represents total number of experiments where $N_{EX} = N_{LE}^{N_{CF}}$

The findings in Table 1 reveal that in most cases, Taguchi metod is used in combination with other methods as a hybrid technique which has yeilded significant improvements in final results specially, for appearance quality optimization purposes.

On the other hand, the average number of control factors recorded in Table 2 is almost 5 and is mainly related to four categories of pressure, temperature, time and velocity/speed as root causes of variation in plastic injection molding.

In Table 3, “M2P2” refers to the medium through which optimization process was supposed to occur, i.e., via material/process parameter selection or mould/product design. Regarding the SNR analysis, the values of \underline{I} (selected) and \underline{O} (NOT selected) are used to refer to the type of SNR. The findings show that, “LIB” is the most frequent type of SNR used, probably due to the defect nature of responses in PIM that need to be as minimized as possible.

5.0 CONCLUSION

In this paper, we have applied citation analysis as one of the most common Bibliometrics methods for scientific analysis of academic literature [19, 20]. The analysis was conducted focusing on seven top optimization techniques used in plastic injection molding industry (PIMI). A total number of 133 unique

papers were investigated during the year 2001 to March 2013 by referring to the Thomson Reuter's Web of Science database. For the first time, triple criteria of chronological trend, geographical dispersion and academic reputation were introduced to evaluate the overall performance and popularity of each method as compared to others.

It was proved that Taguchi, GA, ANN and RSM in total account for % 80 of all the contribution for the research in PIMI based on the 80:20 or Pareto rule. Referring to the findings related to geographical dispersion, it was found that Asia is the centre for research in plastic injection moulding with Taiwan and China having more than % 70 of the world market share. Malaysia was also ranked as the third country in Asia and the fourth in the world after the USA. Regarding the academic reputation, Taguchi and GA received the highest citation and h-index value as compared to the other five methodologies.

And finally, Taguchi method was concluded as a core methodology in PIMI due to being highly compatible with the inconsistent nature of such MIMO processes. On the other hand, TM was also proved to yield much consistent and reliable results when combined with other heuristic methods such as ANN and GA, especially for product and mould design objectives rather than for processing parameters optimization where Taguchi Method (TM) still remains to be the most practical optimization technique.

All in all, it is strongly believed that the findings in this study can provide comprehensive guide and practical implication for top managers, quality/production engineers as well as investors in PIM industry worldwide on selecting the best and most compatible optimization strategy based on a recently calculated feedback of popularity and practicability. As part of the industrial value of the approaches used in this study, which can specially be applicable in the mass production environment of plastic injection molding as a powerful competitive advantage, is to provide the technical as well as managerial insight for selecting the best supply chain components from different parts of the world as a critical value adding factor to the final product with better quality at a reasonable price.

As part of future research, it is recommended to expand this study to investigate the generalizability of the current results by considering specific component shape and material using more advanced Bibliometric methods such as co-citation coupling and bibliographic coupling.

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