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ORIGINAL ARTICLE

Critical factors for the dimensional management system (DMS) implementation in manufacturing industries

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Abstract This paper presents the critical factors that constitute a successful deployment of the dimensional management system (DMS) methodology in manufacturing industries. DMS refers to a process by which the whole integrated product development (i.e. conception, design, manufacturing and inspection) is systematically defined and monitored to meet predetermined dimensional quality goals. A deep research on academic literature was performed to raise 26 factors considered critical for a successful DMS implementation. Professionals who work in this area were surveyed about the importance of each factor, both in a conceptual view and degree of application of this same factor according to their experience. The survey was conducted in two different approaches to provide a clear comparison between these two contrasting aspects. After that, a management model that considers the top-rated factors obtained from the survey results, analysed by statistical multidimensional tools, is proposed. The factor importance/application ranking is a preliminary model which aims at offering a starting point for researchers concerned in continuing this analysis or to offer a guide for industries interested in this methodology.

Keywords Manufacturing · Dimensional management system · Factor analysis · Survey

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1 Introduction

Airplanes, cars and oil platforms are typical products with complex assembly processes, whose manufacturers, due to global competition, are continuously under pressure to boost performance and profitability [1]. Competitive advantage for these manufacturers depends on being able to produce products with increased quality, reduced cost and shorter time-to-market [2]. These companies are also affected by international economic conditions and political uncertainties, which influence both raw material supply and consumer market [3]. To survive in this unstable environment, industrial managers must innovate not only in manufacturing methods but also in the strategy adopted in the integrated product development (IPD) process. Decentralization is a trend adopted worldwide and such a strategy demands that the entire product manufacturing cycle—which, in this context, can be located in different countries—from design to manufacturing and inspection process, occurs unequivocally, considering all aspects associated with dimensional controls. There is no room for individual judgment on the manufacturer or metrologist [4].

Dimensional variation is inherent to the manufacturing process and cannot be fully eliminated. However, this non-compliance can be identified, quantified and analysed and can, in this way, be managed [5]. DMS is the process by which the IPD—design, production and inspection—is defined and monitored to meet dimensional quality targets previously set by customers or market [6]. In this context, the deployment of DMS proves to be essential for companies that operate in global markets [7] in which assembly line cost reduction and performance gains are an essential competitive advantage and ever-needed requirement. This process involves not only technical issues or administrative aspects but also a multidimensional analysis of factors that are critical to the success of DMS deployment process [8].

Concern with dimensional variation is not new. Not even the adoption of concurrent engineering as a way to overcome this non-compliance. Hung, Kao and Ku proposed the new product development (NPD) [9], a quality function development (QFD)-based procedure for generating design alternatives, using partnership collaboration. NPD operates primarily during the product conception phase, generating design alternatives based on manufacturing concerns. Another research in this area was presented by Skander, Roucoules and Meyer, who introduced knowledge synthesis method [10] whose main goal is integrating process capabilities and manufacturing constraints to product design requirements. Their approach makes use of physical models to simulate real-world design attributes in order to produce a collaborative databank of ideal process and manufacturing constraints related to specific designs. Furthermore, there is Nguyen and Martin product design and process manufacturing integration technique [11] that has focused on the concurrent engineering analysis performed in the early design stages in order to uncover eventual no acceptance detail. Nguyen integration method makes use of digital manufacturing to simulate fabrication characteristics and provide preliminary statements regarding this feature.

The innovation presented in this manuscript is the alignment between researchers knowledge and professional expertise to sketch a DMS deployment guideline. Moreover, as highlighted by previous manuscripts [9–11], the focus on dimensional management subject is typically on a single IPD critical stage. The present research proposes a broader analysis, including commitment and leadership attitudes, strategic features, market analysis aspects and manufacturing factors. Under this proposition, this paper introduces two research questions: (1) what are the most important critical factors to the deployment of DMS into metal-mechanical segment companies? and (2) what are the critical factors of greater importance which correspond to those with a higher level of application in the deployment of DMS?

In order to answer these research questions, three main objectives must be highlighted: (1) raise through academic literature the factors that influence a successful DMS deployment in metal-mechanical segment companies; (2) conduct a survey of professionals experienced in DMS deployment, aiming to quantify the importance and application of each factor raised in the literature, and (3) use statistical tools to analyse data from the survey, from importance and application perspectives, making comparisons between them.

The central hypothesis proposed by the authors of the manuscript is that, according to respondents' perceptions, critical factors of greater importance correspond to those with a higher level of application in the deployment of DMS.

2 Literature review

The literature review focuses on factors that influence DMS implementation process. To be considered critical, a factor shall be essential to the organization success on the implementation process [12]. John Rockart coined the term "critical success factors" to define the features that should be constantly and rigorously controlled by management to ensure the strategy success [13, 14]. Table 1 presents factors selected from literature with bibliographical references (ref). Factors were grouped by similarity, according to empirical data.

Table 1 Critical factors for DMS implementation

Factor	Factor description	Ref.
1	Count on senior management commitment and support during DMS deployment	[6, 15, 16]
2	Concurrent engineering team/IPD	[5, 6, 17, 18]
3	Clearly identifies customer's product requirements	[6, 19, 20]
4	Production cost analysis associated with tolerance required by the market	[18]
5	Clear manufacturing strategy	[5, 18, 21]
6	Realistic timetable of DMS deployment process	[18]
7	Effective leadership/problem-solving during DMS deployment	[6, 18]
8	Effective management of risk	[22]
9	Key characteristic (KC) identification based on functional requirements	[6, 23, 24]
10	G&T and product assembly process integration	[5, 6, 18]
11	GD&T training to people involved on DMS deployment process	[6, 17, 25, 26]
12	GD&T international standard alignment (ASME or ISO)	[5, 20, 21, 27]
13	Subcontractors DMS skill policy	[28]
14	Make use of variation simulation 3D tools	[18, 29]
15	Make use of statistical indexes (Cp, Cpk, Six Sigma) to monitor process output over time	[6, 17, 30–32]
16	Metrology (inspection tools) techniques dissemination	[6, 33, 34]
17	Failure mode and effect analysis (FMEA)	[35, 36]
18	Clear communication channels during DMS deployment process	[6]
19	Use of previous projects manufacturing experience	[37]
20	Customer integration	[25, 38]
21	Supplier integration	[38, 39]
22	Flexible approach to change	[21]
23	Reduce shop floor hard tooling necessity	[40, 41]
24	Robust design concept endorsement	[20, 42]
25	Standardized GD&T process adoption	[15, 20]
26	Lean manufacturing philosophy adoption	[17, 43]

The first group is associated with company's management commitment and leadership, which includes management participation and leadership prepared to deal with risks during DMS deployment. In this way, such a procedure depends on senior management support (1) considering training investment necessity, dedicated personnel and other areas involved in IPD commitment [6, 15, 16]. Leadership has to be effective and competent to deal with contingencies that, invariably, arise during implementation [6, 18] (7). Proper risk analysis (8), associated with the activities to be undertaken, is critical to ensure operation success [22]. Finally, it is important to establish adequate and effective communication channels among personnel involved in the process (18) to ensure methodology dissemination throughout DMS set-up [6].

The second group refers to strategy factors and considers both aspects related to people involved in method implementation, the product and its features. In this context, simultaneous engineering concepts (2) are related to resources optimization and IPD [5, 6, 17, 18]. Moreover, standardized dimensional system adoption (25) is a way to ensure repeatability of collected results [15, 20]. Robust design concept endorsement (24), which describes product features, little affected by environmental or operational modifications on production factors. Robust design focuses on the primary functions of the product, thus facilitating flexible designs and concurrent engineering [20, 42]. FMEA (17) is a preventive method to analyse possible system failure modes [35, 36]. Flexible approach to modifications (22) required during DMS deployment ensures suitable results according to strategic target [21]. Finally, concepts related to lean manufacturing (26) make use of tools that enable mapping the value of product flow and provide operational optimization [17, 43].

The next group—market analysis—comprises product perspectives to aspects related to customer interface. In this aspect, an adequate product specification of customer requirements (3) enables proper planning of required production capacity [6, 19, 20]. Moreover, such a market analysis provides suitable product cost in order to satisfy market tolerance demand [18] (4). Another important factor is product key features (9), which is related to product characteristics that cannot be removed or modified, either due to the risk of losing market or to comply with security or performance aspects [6, 23, 24]. Customer participation to DMS (20) in order to optimize product development, aiming to meet market requirements, is the last factor of this group [25, 38].

Subsequent group describes factors related to manufacturing, comprising strategy, planning, techniques and performance level availability and supplier integration. Manufacturing strategy (5) refers to aspects such as requirements, key factors and costs that determine how, where and how often products are assembled [5, 18, 21]. A realistic timetable for DMS deployment (6) provides a dimensional engineer planning over the IPD process in order to optimize workforce, cost and quality [18]. Integration between the concept of geometric dimensioning and tolerancing (GD&T) and manufacturing procedure (10) refers to the systemic use of GD&T theory to ensure an adequate product manufacturing specification perception [5, 6, 18]. The stimulus of 3D simulation tools (14) is another factor to promote—among other benefits—a reduction of the development cycle of new products, frequently avoiding the necessity of building expensive physical prototypes [18, 29]. It also helps verify if specified dimensional requirements are being fulfilled. Process capability indexes (Cp or Cpk) (15) represent the best process performance while operating under normal conditions. These indexes are measured by variation of common causes through statistical control. They are used in Six Sigma philosophy, which identifies problems and try to minimizes the variation in the process [6, 17, 30–32]. Metrology techniques propagation (16) includes measurement procedures, operator-controlled environment and statistical techniques for data analysis, as well as feedback of the results and decision-making about eventual necessary improvement [6, 33, 34]. Supplier involvement (21) is another critical aspect because it makes the identification of product conflicting requirements easier [38, 39]. The frequent use of specific tooling (hard tooling) (23) is related to the plant layout and is contrary to a flexible strategy that includes multifunctional devices and elimination of specific tooling. However, a decision to use or not such devices is strategic because hard tooling is frequently already installed and, starting a new process—in this scenario—becomes unfeasible [40, 41].

Final group consists of factors pertinent to organization's knowledge management, considering a DMS fulfilment. Provided employees represent the main asset of any manufacturing industry, it is important to provide GD&T training to ensure a smooth implementation (11) [6, 17, 25, 26]. Likewise, a natural consequence of skilled participants is a consensus regarding the selection of international standard (11). Mistakes committed in this step may result critical losses [5, 20, 21, 27]. Furthermore, in the last few years, there has been a clear shift towards long-term, commitment-based supplier–customer relationships among the manufacturers. Such strategy is linked to the necessity of an effective subcontractor skill management (13) [28]. Lastly, the reuse of manufacturing experience improves the product manufacturability and, principally, avoids the reoccurrence of design flaws in ongoing or new projects (19) [37].

3 Methodological procedures

The research strategy used by this article's authors was to foster a survey with professionals working with DMS methodology for companies in the automotive, aerospace and oil or those who provide advice in this area. Table 2 presents an overview of the manuscript research methodology divided by steps.

Table 2 Research methodology

Step	Step description
1	Definition of the manuscript hypothesis
2	Literature review
3	Research tool preparation
4	Preliminary survey
5	Conclusive survey
6	Scale consistency analysis (Cronbach' alpha)
7	Inconsistent data removal (box plot analysis)
8	DMS importance/application ranking
9	DMS importance/application ranking comparison analysis
10	Conclusion

The survey methodology was chosen because the analysis aims to understand a large sample behaviour, set in a population by means of a data collection instrument [44, 45]. In addition, questionnaires—the tool used in this survey—constitute an unequivocal and clear research goal translation [46]. Another practical advantage, as evidenced in this research, was the easy integration with DMS professional network and the availability of tools for organizing data collected. With the first, the questionnaires could be shared in foreign DMS user groups while the second simplified the analysis of data collected through an integrated tool.

A preliminary survey was carried out, to ensure a proper behaviour in data collection instrument in a real situation. The preliminary test was conducted with teachers and professionals concerned with DMS. Note that the volunteers who took part in the preliminary test did not participate in the final survey, as this would disqualify the experimental results, characterizing them as preliminary [47]. It is important to highlight that the quantity of factors to be used in the questionnaire has been thoroughly discussed with academics and industrial DMS specialists in this stage. It was agreed that, although there could be more than 26 factors that would lead to a very segregated analysis, they are difficult to be assessed by respondents. Therefore, decision regarding the final questionnaire containing the 26 factors was made by consensus. Further adjustments were made on factor description to turn their understanding easier.

Professionals with experience in DMS deployment process composed the sampling used for this study and were asked to provide information based on their experience. The questionnaire containing 26 factors (Table 1) was divided into two parts: the first (1) asked the participant recounting their perception (grades 1–10) regarding the conceptual factor importance under consideration. The second field (2) requested the perception (grades 1–10) regarding the factor application in the DMS deployment experience. Figure 1 shows an example of question presented to respondents.

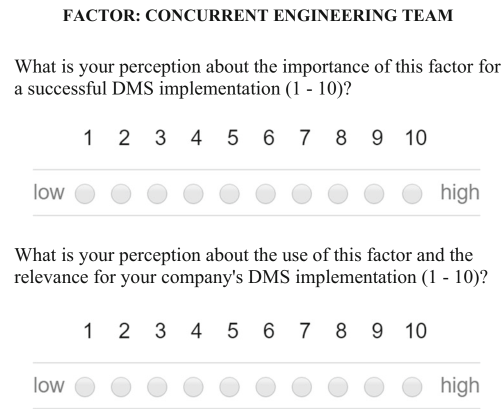

Fig. 1 Box plot format [63]

The collected data were previously validated through two distinctive tools: (1) reliability coefficient—Cronbach's alpha—and (2) outliers' removal—box and whisper plot. The Cronbach's alpha (α) was developed by Lee Cronbach to provide a measure of the internal consistency of a test or scale [48]. The factor is expressed by a number between 'zero' and 'one' and estimates the scale reliability of a questionnaire used in a search by the profile analysis of their responses [49]. Internal consistency describes the extent to which all the items in a test measure the same construct, and hence, it is linked to the interrelation of the items within the test [50]. Internal consistency shall be determined before running the survey to ensure validity of the results [51]. The minimum acceptable value for this ratio is 0.6 [52]. For social research, [53] values above 0.7 are classified as acceptable. Subsequent researches [54] extend this analysis, stating that data that Cronbach's alpha is larger than 0.9 would be very consistent [53, 54]. On the other hand, the box and whisker plot—or box plot—is a tool that visually enables to evaluate the symmetry of the data, dispersion and whether or not data are inconsistent or outliers. Box plot is sometimes called the five-number summary, because the method uses five summary statistics for a certain variable. These summary statistics are shown in Fig. 2.

Values on the box and whisker plot are defined as follows:

- Median—the middle of the data when it is arranged in an order from least to greatest;
- Lower quartile or 25th percentile—the median of the lower half of the data;
- Upper quartile or 75th percentile—the median of the upper half of the data;

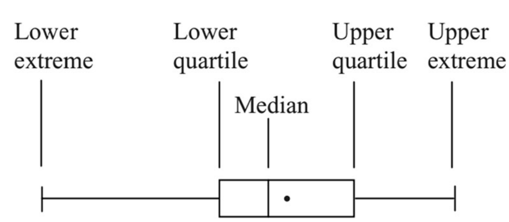

Fig. 2 Example of question

- Minimum value—the smallest observation value;
- Maximum value—the largest observation value.

Outcome for a box plot analysis is as follows:

- The box portion of the box plot includes 50 % of the data;
- The whiskers extend to the minimum and maximum data values;
- Data outside the upper to lower interval can be considered outliers.

For the calculation of both factors, authors have used Statistical Package for Social Sciences software (IBM/SPSS) by making use of the functions (1) Reliability analysis, model cronbach's alpha and (2) Graphs, legacy dialog, box plot.

3.1 Data analysis

Multivariate analysis refers to the statistical techniques that simultaneously analyse multiple measurements on individuals or objects under investigation [55]. Authors of this manuscript have decided to guide the current analysis by exploratory factor analysis to assess the dimensionality, reliability and validity of the variables [56].

Exploratory factor analysis (EFA) consists in a branch of multivariate analysis that provides tools for analysing the structure of the correlations among a large number of variables by defining sets of variables that are highly interrelated—the factors. Provided the objective of the factor analysis in this research is to identify logical and importance combination between the variables and better understand the factors interrelationships, the exploratory analysis shall provide an empirical basis for judging this analysis [55].

Operationally, after outlier's data removal, a principal component analysis was performed for the remainders' answers. Subsequently, these data were submitted to an Exploratory Factor Analysis (EFA) unifactorial in order to create a 26-factor ranking according to their importance and application for DMS deployment [55, 57, 58]. The EFA was performed using the Statistical Package for Social Sciences software (IBM/SPSS). Importantly, the factor scores could be used as a matter of scale because all the answers are on the same basis (1–10) [59]. For both importance and application criteria, the parameters used were as follows: date, analysis, dimensional reduction, analysis factor, extraction, principal component analysis, correlation matrix, varimax, rotated solution, and missing value (replaced with mean) [60].

3.2 Sample characterization

To characterize the respondents' sample, it was considered the industry branch and the respondent's experience time with DMS methodology.

Table 3 shows the sample composition by an active industry branch. It is found that the aerospace and automotive branches account for almost 80 % of the sample studied. Another important aspect is that the consulting branch includes respondents who filled out the form as academics.

Table 4 shows the sample composition by the experience time with the DMS methodology. It is noticed heterogeneous profile, however, in the sample worked, prevails professionals with medium/high experience, which may have contributed to the high maturity of responses, attested by the high coefficient of Cronbach's alpha.

4 Results and analysis

4.1 Data internal reliability analysis and outlier answers

In order to perform a reliability test to the collected data, it is examined how closely related these data behave as a group. Such an internal consistency is considered a measure of scale reliability assessed through Cronbach's alpha coefficient. For DMS importance, Cronbach's alpha is 0.903, and for DMS application, the same coefficient is 0.917. According to Gliem and Gliem (2003), such a coefficient indicates that collected information for both DMS criteria represents very consistent data [54].

DMS importance criterion outlier analysis is shown in Fig. 3. Respondents numbered 31, 32, 45, 51, 52, 54, 55, 56, 59, 70, 80, 84, 85, 86, 87 and 107 were considered inconsistent. Decision on how to proceed with outliers is up to the analyst: While working with small samples, researcher could decide on removing only inconsistent responses. In this research, however, authors have chosen to delete all data from interviewees who had at least one of its answers not compatible. The reason was the irrelevance of incoherent answers—16—compared to the original sample size—113 respondents [53]. Moreover, the remaining samples—97 respondents—allow a good fit to the proposed models [61, 62].

DMS importance criterion outlier analysis did not detect any pattern that distinguishes this classification. Among the 16 respondents considered outliers, there are aerospace, automotive and consulting industry representatives that account for 97 % of the original sample. The absence of outliers from oil industry could be a consequence of the small number of interviewees of this industry branch—three people or 3 % of the sample.

Regarding experience with DMS methodology, inconsistent respondents vary from the newest—2 years—until very experienced professionals—16 years working with DMS methodology. Average of that experience time was 7.2 years—close to the average of the original sample time, 6.8 years. Arguments presented above leads to the conclusion

Table 3 Sample composition by industry branch

Industry branch	Frequency	Percent
Aerospace	56	49.6
Automotive	34	30.1
Consulting	20	17.7
Oil	3	2.7
Total	113	100.0

that further study is required to come to a clear conclusion about a possible characterization of outliers.

DMS application criterion outlier analysis has similar examination outlined in Fig. 4. Respondents numbered 31, 32, 45, 56, 57, 59, 70, 81, 86, 87, 91, 95, 99, 103, 104, 105, 107, 108, 110 and 113 were considered discordant. Here again, authors decided to delete all data from respondents who had at least one of its answers considered incompatible. The number of remaining sample—93 respondents—was also considered suitable for analyses [61, 62].

Similar to importance analysis, the outlier examination for DMS application criterion did not detect any pattern that distinguishes this classification either. Concerning experience, outliers involve from new employees—2 years—until very experienced—16 years working with DMS methodology. Average of that experience time was 6.1 years old—close to the average of the total sample—6.8 years.

4.2 DMS importance criterion ranking

Exploratory Factor Analysis (EFA) was used to build a ranking of factors considered relevant for a successful DMS implementation. After removal of outlier data, importance criterion sample resulted in 97 respondents. EFA scores were organized and thus obtained the ranking shown in Table 5.

Key factors identification (9) scored 1.9. It is, therefore, the most important aspect under importance criterion.

Afterwards, factors (12), (3) and (11) get clustered, reflecting variables with similar underlying structure. Such a similarity may be related to the relationship of all factors with product improvement processes. Standardization of dimensional engineering standard (12) reflects the concern with deviations caused by the use of different criteria. Clear identification of customer requirements (3) occupies third place and reflects adherence to the criteria analysed. Count with a technically prepared team for DMS accomplishment (11) appears as a relevant aspect.

Subsequently, factors (2), (14), (1), (16) and (10) also cluster, although in a lower factor score level. In this group, concurrent engineering concepts (2), with a score of 1.011, is slightly ahead. Making use of 3D simulation tools (14) in the sixth place confirms respondent's maturity considering the importance given to such new-trend DMS application. An underlying structure to the factor related to senior management support (1) demonstrates, in principle, consistency regarding evaluation approach. 3D simulation tools demand dedicated people focused on dimensional analysis, in addition to the cost of training and acquisition of specific software licenses. All this require senior management approval similarly to DMS implementation process.

Regarding metrology technique factor (16)—eighth place—and GD&T concept integration and assembly process (10)—ninth—reinforce the interviewee's DMS knowledge due to the these factors specificity.

A clear manufacturing strategy (5) occupies the tenth place with factor score 0.299. Such a factor represents a deflection point from which the score values decrease markedly.

Between (26) and (6), there is an inversion of the factor signal, becoming negative. Provided factor score is a combination of all variables, it assumes both positive and negative values. Score is positive when variables with high weight have an underlying factor structure to the set of variables collected. On the other hand, score is negative when variables with high weight do not have such a characteristic.

Furthermore, on the factors' negative side, there is also cluster arrangement among (18), (24), (13), (25) and (4). After (8), there is an upward curve—(21), (15), (17), (20), (23), and (7)—to the most negative factor represented by (19).

Table 4 Sample composition by DMS experience time

Time (years)	Frequency	Percent
2	7	6.2
3	12	10.6
4	14	12.4
5	12	10.6
6	16	14.2
7	12	10.6
8	14	12.4
9	4	3.5
10	5	4.4
11	2	1.8
12	6	5.3
13	5	4.4
15	2	1.8
16	2	1.8
Total	113	100.0

4.3 DMS application criterion ranking

Similarly, unifactorial Exploratory Factor Analysis (EFA) was used to build a 26-DMS application factor ranking. EFA scores were organized and thus obtained the ranking shown in Table 6.

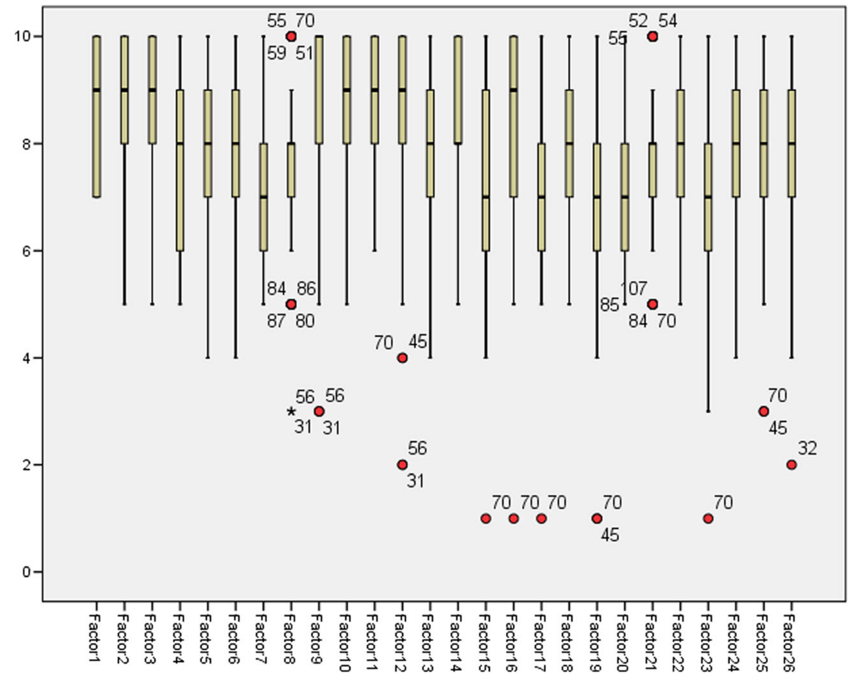

Fig. 3 DMS importance criterion—box plot analysis

For application ranking, the upmost importance of (11) is not as obvious as in importance analysis. In addition, factor (9) regularity is remarkable because it not only occupies the first position on importance ranking but also remains on the second place for application analysis.

Factor (10)—integration of GD&T process—has similar concerns to key factor product identification (9), and perhaps both have similar underlying structures.

Factors (12), (14), (3) and (2) get clustered and reveal an interrelation between these factors according to the interviewee's perception. Comprehension regarding importance on the use of single dimensional engineering standards (12) is noteworthy because that reflects significant quality commitment. Remaining clustered factors are related to product quality improvement.

Factor (1)—support of senior management to DMS implementation—gathers with factors (16) and (5). Similar to what

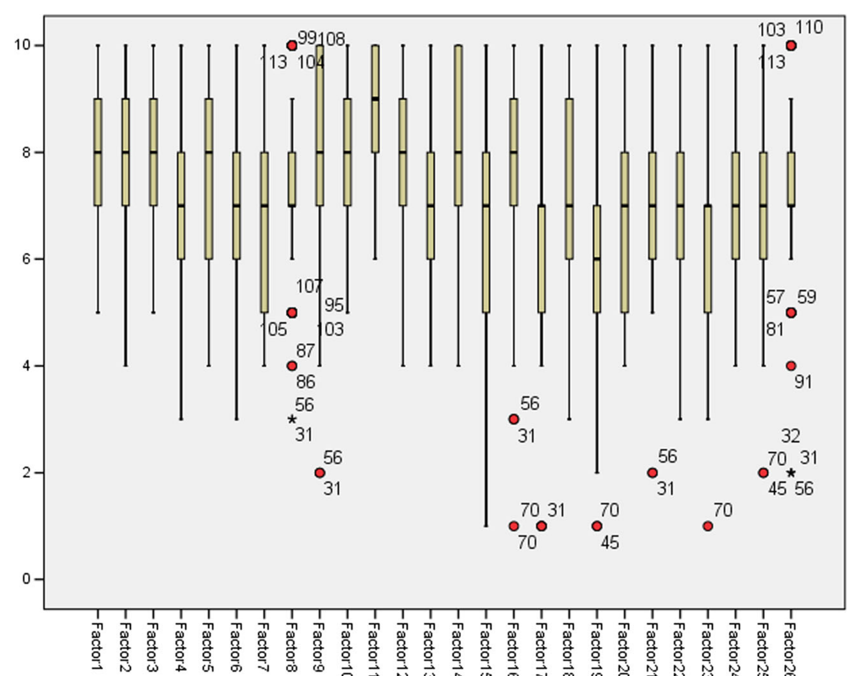

Fig. 4 DMS application criterion—box plot analysis

Table 5 DMS importance criterion ranking

Ranking	Factor	Score	Factors brief description
1	9	1.9	Key characteristics (KC)
2	12	1.3	Align GD&T international standard
3	3	1.3	Customer's product requirements
4	11	1.3	GD&T training
5	2	1.0	Concurrent engineering
6	14	1.0	Use of simulation 3D tools
7	1	1.0	Management commitment
8	16	1.0	Metrology dissemination
9	10	0.9	GD&T and product assembly process integration
10	5	0.3	Manufacturing strategy
11	26	0.0	Lean manufacturing
12	6	−0.1	Realistic timetable
13	18	−0.2	Communication channels
14	24	−0.3	Robust design
15	13	−0.3	Subcontractor DMS skills
16	25	−0.3	Standardized process
17	4	−0.4	Production cost analysis
18	22	−0.5	Flexibility
19	8	−0.7	Management of risk
20	21	−0.7	Supplier integration
21	15	−0.9	Statistical indexes (Cp, Cpk, Six Sigma)
22	17	−1.1	FMEA
23	20	−1.2	Customer integration
24	23	−1.2	Hard tooling
25	7	−1.3	Leadership/problem-solving
26	19	−1.8	Reuse manufacturing experience

Table 6 DMS application criterion ranking

Ranking	Factor	Score	Factors brief description
1	11	2.1	GD&T training
2	9	1.7	Key characteristics (KC)
3	10	1.5	GD&T and product assembly process integration
4	12	1.1	Align GD&T international standard
5	14	1.0	Use of simulation 3D tools
6	3	1.0	Customer's product requirements
7	2	0.1	Concurrent engineering
8	1	0.7	Management commitment
9	16	0.6	Metrology dissemination
10	5	0.4	Manufacturing strategy
11	26	0.0	Lean manufacturing
12	18	−0.1	Communication channels
13	24	−0.2	Robust design
14	8	−0.2	Management of risk
15	25	−0.5	Standardized process
16	13	−0.5	Subcontractor DMS skills
17	22	−0.5	Flexibility
18	6	−0.6	Realistic timetable
19	4	−0.6	Production cost analysis
20	21	−0.9	Supplier integration
21	20	−0.9	Customer integration
22	17	−1.0	FMEA
23	23	−1.2	Hard tooling
24	15	−1.2	Statistical indexes (Cp, Cpk, Six Sigma)
25	7	−1.2	Leadership/problem-solving
26	19	−1.4	Reuse manufacturing experience

has been explained for importance criterion, these factors' similarity is the financial support involved in all three factors.

Adoption of lean manufacturing concepts (26) presents a sharp drop in the factor score. The reason may be a steep reduction on the remaining factor application level.

From factor (18), concerning the clear definition of communication channels, there is an inversion on the ranking value, becoming negative. As previously highlighted, a score is negative when heavy weighted variables do not have an underlying factor structure to the set of collected variables.

Factors (25), (13), (22), (6) and (4) are clustered, reflecting variables with similar underlying structure, even though negatives.

Remaining factors—(21), (20), (17), (23), (15), (7) and (19)—form a descending application score series.

4.4 Factor ranking comparison—importance and application criteria

Table 7 compares and contrasts importance and application criteria factors according to respondent's point of view. Furthermore, in "DELTA" column, it is highlighted the gap between conceptual importance and application level of factors is considered critical for a DMS implementation process. Positive "DELTA" reflects an increment on factor importance in DMS deployment process, as well as negative value expresses reduction of this magnitude on the interviewee's perception. Remarkably, it is noted that the first ten factors are the same for both criteria, in a different order though.

For a 26-factor importance and application comparison, the results could be summarized as follows: ten of them had their ranking increased, six remained with the same score and, finally, ten suffered a reduction. In addition, column "DELTA" analysis reveals significant changes in importance ranking according to respondents view, noticeably factor (10)—increase of 6—factor (6)—reduction of 6—and factor (8)—increase of 5.

Factor (10) had a 6 position ranking rise while evaluated under the application criteria. Such a difference could represent an inconsistency between the criteria under analysis, or a subsequent confirmation of the factor importance during DMS implementation experience. Indeed, integration of GD&T concepts with product assembly processes tends to be noticed after non-conformities in production are generated by the absence of such integration.

Nevertheless, factor (6) had a 6 position ranking reduction while evaluated under the application criteria. Such a reduction may be related to the interviewee's perception that such requirement—implementation schedule—may be under control in another factor.

Table 7 Factor ranking comparison—importance (‘I’) and application (‘A’) criteria

Factor	Ranking ‘I’	Score ‘I’	Ranking ‘A’	Score ‘A’	DELTA	Factors brief description
9	1	1.9	2	1.7	−1	Key characteristics (KC)
12	2	1.3	4	1.1	−2	Align GD&T international standard
3	3	1.3	6	1	−3	Customer’s product requirements
11	4	1.3	1	2.1	3	GD&T training
2	5	1	7	0.1	−2	Concurrent engineering
14	6	1	5	1	1	Use of simulation 3D tools
1	7	1	8	0.7	−1	Management commitment
16	8	1	9	0.6	−1	Metrology dissemination
10	9	0.9	3	1.5	6	GD&T and product assembly process integration
5	10	0.3	10	0.4	0	Manufacturing strategy
26	11	0	11	0	0	Lean manufacturing
6	12	−0.1	18	−0.6	−6	Realistic timetable
18	13	−0.2	12	−0.1	1	Communication channels
24	14	−0.3	13	−0.2	1	Robust design
13	15	−0.3	16	−0.5	−1	Subcontractor DMS skills
25	16	−0.3	15	−0.5	1	Standardized process
4	17	−0.4	19	−0.6	−2	Production cost analysis
22	18	−0.5	17	−0.5	1	Flexibility
8	19	−0.7	14	−0.2	5	Management of risk
21	20	−0.7	20	−0.9	0	Supplier integration
15	21	−0.9	24	−1.2	−3	Statistical indexes (Cp, Cpk, Six Sigma)
17	22	−1.1	22	−1	0	FMEA
20	23	−1.2	21	−0.9	2	Customer integration
23	24	−1.2	23	−1.2	1	Hard tooling
7	25	−1.3	25	−1.2	0	Leadership/problem-solving
19	26	−1.8	26	−1.4	0	Reuse manufacturing experience

Finally, factor (8) had a 5 position ranking increase. An effective risk analysis is fundamental while implementing manufacturing strategy models such as DMS methodology, which is treated in this research.

5 Conclusion

As a conclusion of this research, authors believe that the main objectives proposed were fully achieved: submission of 26 factors considered critical for a successful DMS implementation according to related literature and design and implementation of a survey with professionals who worked with DMS deployment in automotive, aerospace, oil and consultant industries.

The survey outcome led to the development of a factorial ranking considering two criteria: factor conceptual importance and degree of application of the same factor considering DMS implementation experience of the interviewees. Such a guideline aligns DMS researchers’ knowledge—apprehended from literature review—and professionals’ experience—assessed on the survey. The authors have also compared and contrasted the two criteria to highlight differences and analyse any possible discrepancy in the research methodology.

Research questions proposed in the introduction of this article were also answered.

1. Twenty-six critical factors for a successful DMS implementation are classified according to importance and application criteria, based on DMS professional analysis.
2. According to the survey results, there is no compulsory relationship between factors considered more important and those with the highest degree of application.

All things considered, it seems reasonable to assess the value of the results presented, notably due to the high level of complexity involved in DMS factor readjustment. The ease of understanding opens the possibility to broaden the sample.

This analysis closure becomes an opening to researchers willing to improve the theme presented or even provide a preliminary model for companies that are interested in implementing DMS methodology. The results of the exploratory factor analysis performed on factors considered critical for a DMS deployment can even be used by other academics in their researches.

However, some limitations are worth noting. Although hypotheses are supported statistically, the sample has not covered the full range of industries and that could affect the results. Future work should therefore include a conceptual implementation in order to measure the consequences of each factor in the IPD.

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