INTEGRATED DECISION SUPPORT SYSTEM FOR SELECTION OF RP PROCESSES

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Abstract

This paper describes an 'Integrated Decision Support System for the Selection of RP Processes (IDSSSRP)'. The basic methodology proposed in the IDSSSRP is a Sigma approach towards benchmarking of the Rapid Prototyping (RP) processes. It characterizes a RP process by using benchmarking and the sigma approach to assess its capability compared to its potential. Although the six-sigma approach has basically been a management concept and the success of its implementation has been on process time reduction and quality improvement, this paper adopts the use of six-sigma tools and benchmarking in the characterization of RP processes. Apart from geometrical benchmarks, other benchmarks include mechanical benchmarks and process benchmarks. Benchmarking individual RP processes facilitates standardization and reduces variability in the prototypes produced by the processes. Following standardizations of geometrical, mechanical and process benchmarks, a saturated database can then become very useful in providing decision support to the end user on a particular process as well as a source of information for benchmarking new RP machines. A case study of the benchmarking process developed on the Direct Metal Laser Sintering-Selective Laser Sintering (DMLS-SLS) RP process is presented using the proposed approach. This paper also outlines the working and implementation of a web-based decision support system based on the IDSSSRP.

Key Words: Benchmarking, Six-sigma, Decision support, Process optimization, Process characterization, Saturated database

Introduction

Rapid Prototyping is currently a popular technique in the manufacturing industry. It is based on a material additive process for the fabrication of prototypes and is different from the conventional manufacturing techniques, which are material removal processes. The proposed IDSSSRP offers advice on various RP processes/ systems based on the benchmarking exercise. Although an old concept, benchmarking is recently gaining much attention in manufacturing when a particular process or a system based on that process needs to be evaluated. A benchmark also becomes crucial in its ability to recognize a particular process or a system to meet up with a certain set of requirements that are established to be the industry set standards. In the RP industry however, a generic benchmark that establishes standards in terms of evolving prototypes with the desired dimensional accuracy, form, fit and surface accuracy is yet to be established. The main purpose of the paper is to highlight the overall procedure involved in evolving generic RP benchmarks (i.e. geometrical, mechanical benchmark parts and process benchmarks), and using the benchmarked results for decision support. A generalised integrated decision support system for the selection of RP processes is proposed for evaluating RP processes and the systems based on those processes. The basic methodology proposed is a sigma approach towards benchmarking of the RP processes. It is important to mention here that the proposed idea is yet to be fully realised, however case studies done on the DMLS-SLS process/machine are a proof for the validity of the proposed approach.

Methodology

The proposed methodology in the IDSSSRP is a six-sigma approach in benchmarking the RP processes. The combination of the benchmarking in setting standards and six-sigma to minimize the redundancies in a given process has been proven successful and feasible by a study on the DMLS process.

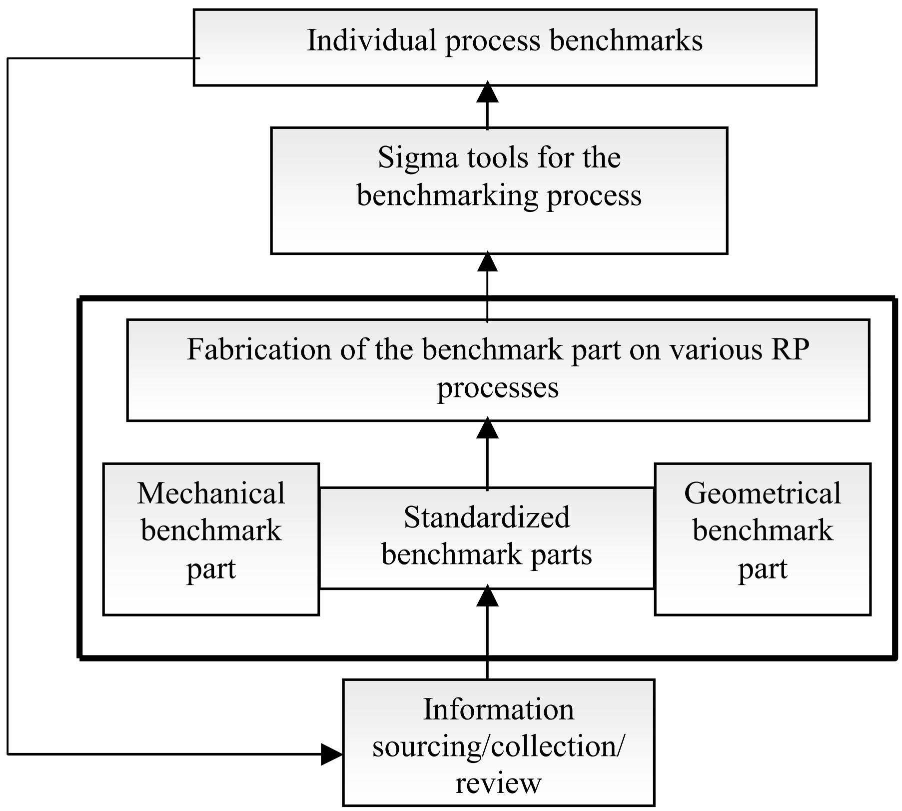

Fig 1. Flow chart for an integrated benchmarking process plan

Figure 1 gives an overall view of the integrated benchmarking process plan. It first starts with the information sourcing of various RP processes, system capabilities, etc from the RP industry. A good understanding of current standards, if available could initially help to visualize the importance of a particular process. Although several benchmarks (benchmark parts) are available in the RP industry, the aim here is to highlight the importance of standardized benchmarks. We suggest that there just should not be just a geometrical benchmark part or a mechanical benchmark part but also standardized benchmarks for the various processes and the measurement techniques as well. It implies that after standardized geometrical and mechanical benchmark parts are finalised, they will have to be built on various RP systems to establish related RP process benchmarks. A standardised measurement procedure should also be practised so as to reduce the inconsistency and variability when determining the results of fabrication on an RP system or process.

The proposed approach can provide standardized benchmark parts for evaluating the geometrical and dimensional accuracy and mechanical properties of prototypes produced via standardized benchmarked processes and verified from benchmarked measurement techniques. As mentioned earlier, the standardized benchmarked process could be established by fabricating the benchmark part on the RP systems to identify the process that could lead to the benchmark part being fabricated with the best accuracy and surface finish.

The benchmark part is subjected to recalibration when there are changes and improvements in the technology associated with the specific process. The benchmarking exercise is therefore a continuous process and is important to update the developments in the technology.

RP Benchmarking Exercise

A generalised benchmarking approach consists of ten steps in five phases according to Camp R.C [1]. The basic five phases are adopted with modification to meet the requirements in benchmarking for rapid prototyping.

Planning

The first step is to identify what is to be benchmarked and which RP practices are to be studied and its source of comparison, if any. For comparisons some sort of a performance measurement of the various RP processes and systems has to be identified to ultimately decide on employing a particular RP process, machine or material in the realization of the final prototype. To aid this performance evaluation in general, standardized benchmarks are considered important, and for purposes of rigorous investigation of a particular RP process/ system, there can be an individual standardized geometrical, mechanical and process benchmarks. Details on the benchmarks can be referred from Wong [2].

Identifying comparative processes: A source for comparison has always been an important aspect in the benchmarking exercise of a particular industry, technique or method. In the RP industry the idea is to compare across the various RP processes/systems in the order of their performance exhibited in building benchmark parts. Comparisons have to be done on the various RP techniques available in the industry, to mention a few like the SLA, SLS, FDM and the LOM with respect to a process that could lead to a prototype with the best geometrical accuracy and mechanical properties. To ensure consistency for comparison purposes benchmark parts have to be fabricated on each RP process including systems based on the process.

RP data collection and validation: A careful investigation had to be made to collect and analyse the different processes/systems with current procedures in the fabrication of a prototype. The information can be obtained from RP companies or alternatively from various RP bureau services, including the very important hands-on experience of RP operators. The best process that could lead to a better prototype (benchmark part) can ultimately be reiterated to establish it as a standardized procedure for particular processes in delivering a good prototype. The idea is to rate and rank the processes in some order of performance. Standardised individual benchmark parts for the geometric accuracy and mechanical strength could further assist in measuring the efficiency and performance of a particular RP process. After the data has been collected some sort of validation has to be made to ensure the consistency of the data for comparison and verification purposes

Analysis

Determining current performance gap: Take for example two prototypes of the benchmark part are fabricated from two different machines, but similar configuration, one prototype can turn out to be better than the other. In such case, the performance of both systems and more importantly the processes based on those systems, have to be analysed carefully to determine the performance gap and obviously adopt the best practice that could realize a better prototype. The basic aim is to identify the gap between the new approach and that of the other practices.

Integration

A database can be created to document the findings from the benchmarking exercise and integrated to a web-enabled decision support system that can offer the end user support and suggestions based on the benchmarked procedures. This could also serve the purpose of communicating the findings to gain acceptance, thereby establishing the level of future performance to the organizations using RP technology.

Action

This is one of the most important phases to establish the credibility of the proposed approach where an experimental verification is important to identify the best process in realising a prototype. By careful implementation of specific actions and monitoring progress vital data could be obtained on best practices that could be later established as standards. Development, implementation and monitoring of action plans could be suggested to maturity with the success expected in the proposed approach of IDSSSRP.

Maturity

This is the final stage when the expected result through benchmarking will be communicated for practice by the RP users. In other words this is the final phase in which the best practices are fully integrated into processes.

RP Benchmarking and performance measurement

Benchmarking is not a measurement by itself but also a process of establishing the gaps in performance and as such ensuring that an action plan is put in place to close identified gaps [3]. In Fig 2, the ladder model emphasises on the generalised actions that are to be taken in process benchmarking to close the gaps in performance. It starts with the actual planning, which is an important step to understand the currents standards if any or setting an initial standard for comparison purposes. A rigorous information sourcing is crucial at this point. After the standards are being set, the performance of the various RP processes or systems based on those processes for example can be compared across so that corrective actions can be taken accordingly based on comparisons with the standards. If the performance is better than the existing standards set, the standards should be replaced accordingly. The benchmarking is always a never-ending improvement. As mentioned earlier initial benchmarks need to be set as a standoff for more generic comparisons in the case of the RP industry.

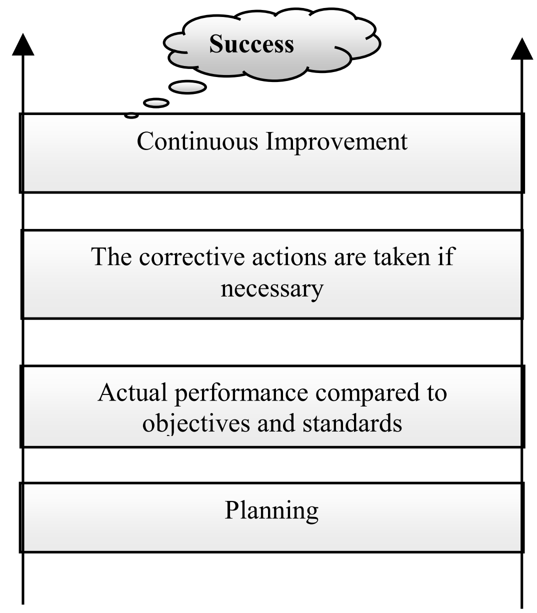

Fig 2. Action Ladder model in Benchmarking

A Sigma Approach to RP Benchmarking

Six-sigma is basically a process quality goal that comes out of statistical probability measurement and process capability techniques. There are numerous six-sigma tools, both experimental and statistical, to analyse a process [4]. We propose the use of six-sigma tools in the benchmarking exercise to identify standardised processes in delivering prototypes. Since experiments form the core of the RP benchmarking process, it is important to validate the approach proposed and also to measure and verify the results acquired from systems based on a particular processes. In our approach the geometrical benchmark part designed will have to be fabricated on different RP systems and a best process is to be identified. That could lead to the benchmark part being fabricated with the best geometrical accuracy and surface finish. In parallel, however, a mechanical benchmark part can also be fabricated as well, to identify the best process that could lead to the benchmark part to have the best set of mechanical properties. Note that there can be several factors that need to be optimised and controlled in order to get to a so-called best prototype, so it is best to use the six-sigma process analysis to optimise the critical factors. The RP benchmarking could be a time consuming and tedious task but once the benchmark is established then the subsequent work can get simpler. A case study on our DMLS-SLS process is highlightened to demonstrate the feasibility of the proposed approach. This study serves to demonstrate the feasibility of the proposed approach on optimising new processes and systems based on the benchmarking exercise.

Case Study on the DMLS-SLS Process

The case study was done on a specially developed DMLS-SLS machine to demonstrate the proposed approach. The DMLS system is mainly a metal sintering machine and has not been successful in building prototypes with a specific plastic powder. This was evident when an attempt was made to build the geometrical benchmark part on the DMLS system. The process was far away from with the limits of a sigma process. The solution to this problem was to initially study the process thoroughly and then identify the key factors that directly influence the quality of the resultant prototype. Apart from identifying the factors, it was also important to identify procedures for a smooth process as a whole. Screening experiments helped us to resolve some of the problems associated with the use of the plastic powder sintering, such as choice of base plates, necessity of powder pre-heating, reshuffling the operation sequence of the powder feeder cylinder, part bed cylinder and scraper movements in order to reduce excess friction causing the parts to fail.

Considering the whole process, our objectives (target) could be summarised as follows:

- To reduce the number of failed parts (good benchmarks parts to be fabricated)
- To identify a smooth process of fabrication.
- To optimise the process for the best or optimised results.

Table 1: Breakdown of the Control factors

List of factors	**Important factors**	**Experimental Control factors**	**Levels**		
Temperature	Laser power	Laser power	**20**	25	30
Scaling	Scanning speed	Scanning speed	**1200**	1400	1600
Offset	Scrapper Speed	Layer thickness	0.2	**0.1**	0.15
Material	Layer thickness	Part bed temperature	35	40	45
Slicing	Part bed temperature				
Scanning speed	Scanning pattern				
Laser power	Hatch size				
Inert gas					
Layer thickness					
Part bed temperature					
Scrapper speed					
Scanning pattern					
Hatch size					
Part placement parameters					
Build package settings					

Taguchi's L 9(3^4) Orthogonal Array

Exp. No	Control Factors			
	Temperature	Laser power	Layer thickness	Scanning speed
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Factor levels	**Values**
1	- Default
2	Default
3	+ Default

In the designed experiments two quality characteristics such as g*eometrical accuracy* in terms of (% deviation) in mm from the nominal dimensions and *surface finish* (Ra, least value desirable) in µm were used as response factors during the experiments. If the critical factors (and their interactions if applicable) are identified, then these factors can be tuned accordingly to make the noise factors insensitive. Apart from identifying an optimized set of parameters, the aim was also to identify a tuned process (benchmarked process) that would help the RP users to follow a standardized procedure accordingly based on their part to be prototyped.

The screening and selection of factors were done using six-sigma tools. The purpose of using six-sigma tools was to deduce and reduce flaws in the process. Table 1 lists the various factors and the reduction to a crucial few that can be used to control the DMLS-SLS process as a whole. The identification of the critical factors allows the DOE to get an optimised scaling of factors that will give the best output with least or negligible influence of noise. In our case study the initial choice of factors was done using tools like Ishikawa "fish bone" diagram and quality function deployment (QFD). Ishikawa "fish bone" diagram was useful to initially identify some of the many potential causes of the variability in the DMLS-SLS process. A QFD was later performed based on the general understanding of the probable factors that could be responsible directly or indirectly in shaping the final prototype in the DMLS-SLS process. A DOE was performed based on the orthogonal array and experiments were done by fabricating the benchmark part, to identify the best setting of control factors with desirable response in terms of geometrical accuracy and surface finish. On implementing the proposed approach on the DMLS-SLS process for plastic powder, the part failures were considerably reduced and the performance was within the limits from the target.

Results and Discussions

On the completion of the experiments measurements were made on the fabricated benchmark parts using a co-ordinate measuring machine (CMM). CMM part programming was used to ensure accuracy, consistency and an efficient comparison. Minitab was used in the statistical analysis of the raw data from the measurements. In our experiments since we were interested on the influence of the control factors on the responses, namely geometrical accuracy and surface finish, it was important to analyze the levels of those factors from the experiments.

The graph in Fig 3 shows the main effects for surface roughness. The main effects plot is most useful when several factors are involved. By comparing the changes in the means level, we can identify those factors that influence the response the most. A main effect is present when different levels of a factor affect the response differently. Also for a factor with different levels, we can find which level increases the mean compared to the other levels. This difference is a main effect.

Since our objective is to reduce the surface roughness, or in other words to have a good surface finish, it can be interpreted from the graph on main plots that the optimised setting (reducing Ra) for prototyping parts from this particular plastic material will include a layer thickness of 0.15mm or higher, medium laser power of about 25-30W, medium scan speed of about 1400 mm/s and a low to medium temperature setting.

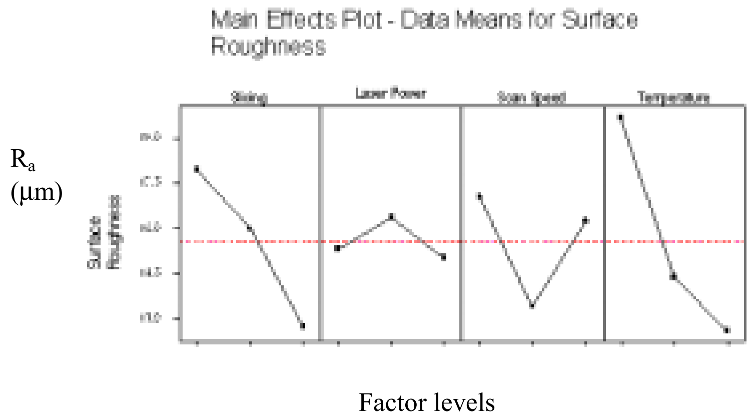

Fig 3. Main plots-data means for surface roughness

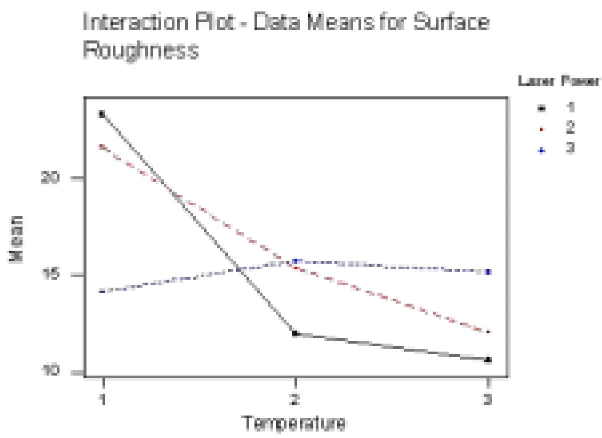

Fig 4. Interaction plots for laser power and temperature

The interaction plots for Laser power and temperature in term of data means of surface roughness are as shown in the Fig 4.

The following figures show the pictures of the benchmark parts before (Fig 5) and after (Fig 6) the application of the proposed approach on the DMLS-SLS process.

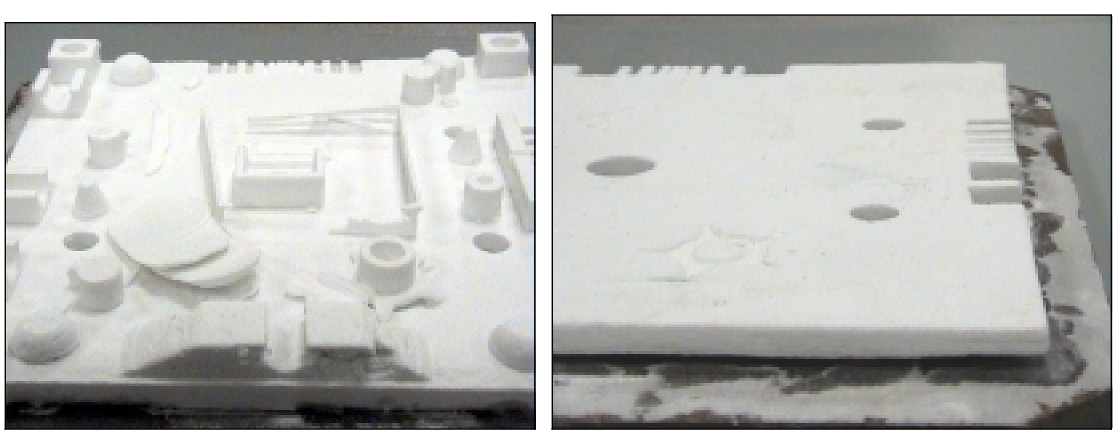

Fig 5. Failed benchmark parts

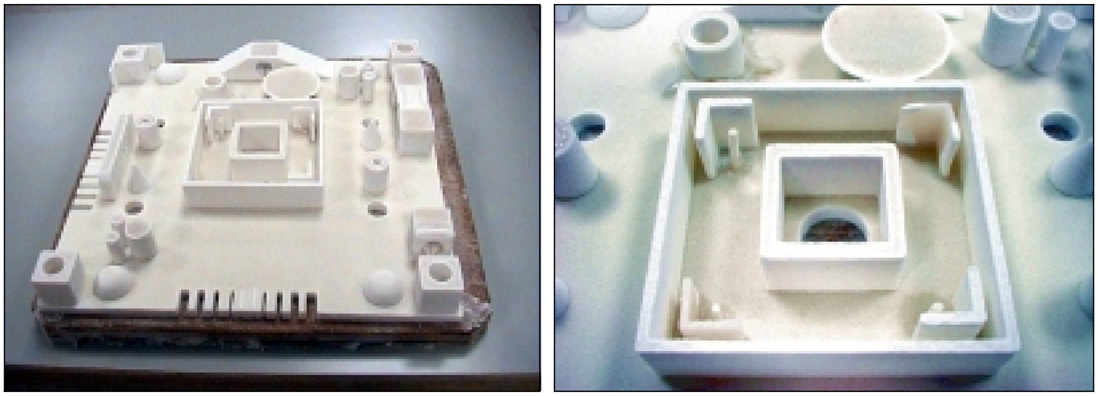

Fig 6. Benchmark part built with a clear profile showing some of the pass/fail features

The failure of the parts was mainly due to improper setting of the control factors, which was later overcome from the identification of their proper setting from the designed experiments. Based on the measured data, optimizations were incorporated in the software in terms of scaling factors and laser beam compensations to arrive at the desired dimensional accuracy. It is evident from Fig 6, the optimized DMLS-SLS process to fabricate benchmark parts with a good surface finish, also improves the clarity and dimensional accuracy of the features being built.

Implementation of IDSSSRP

At the end of the day the findings have to communicated to the users so that iterations can be done to finalize the benchmarks and offer support to the end users. The following Fig 7 presents a framework of the main modules in the implementation of the IDSSSRP.

RP knowledge database:

The RP knowledge database is the central repository that contains general information of the RP industry. It contains information about the different RP processes, systems based on those processes and also the various materials that are used in the various process/systems for the realization of the prototypes. In addition it also includes information on service bureau for various prototyping tasks.

RP benchmarking /standardizations:

This is the core part of the proposed approach which comprises of a search for the industry standards and evolving generic benchmarks for standardized evaluation of the various RP processes/systems. Additional information on benchmarking for performance evaluation of RP systems could be referred to in [2].

Experimentation:

A series of experiments have to be done by fabricating the standardized benchmark parts to identify the best process in realizing the prototype. To accomplish this, action plans have to be developed. Six-sigma tools can aid in the development of action plans. By the implementation of specific actions and monitoring progress, vital data could be obtained on a best process that could be established as a standard.

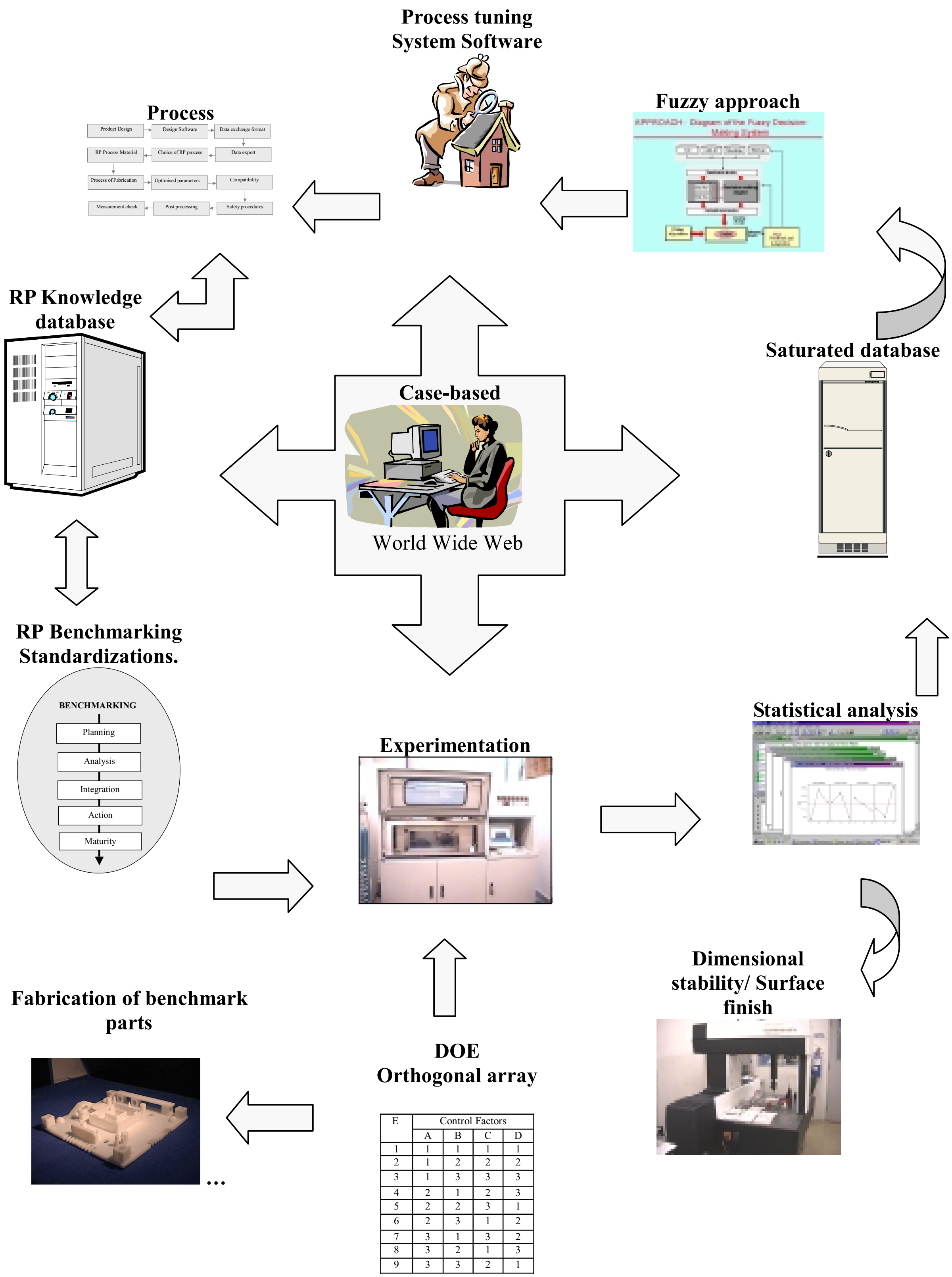

Fig 7. System Architecture for a web based IDSSSRP

Statistical analysis:

The results in terms of quantitative measurements that are obtained by the fabrication of the standardized benchmark parts should be statistically examined and recorded. As in the case of the geometrical benchmark part, the quality characterization will be in terms of the dimensional accuracy and surface finish. Apart from parametric optimizations of particular RP processes to evolve optimized process benchmarks, a dictated statistical analysis procedure will additionally aid comparisons across capabilities of various RP techniques.

Saturated database:

This is the collection of vital and assorted information that is obtained by the act of the benchmarking exercise. This module can be an independent one or can alternatively form a core part of the Central Knowledge database. The saturated database is basically to offer decision support with information that is obtained by benchmarking and standardizations.

Intelligent analysis:

The purpose of benchmarking and standardizations are to offer more consistent and rigorous operating conditions in the RP industry. As an essential part of the benchmarking exercise is to offer decision support, the saturated database and the central knowledge database work to complement each other in offering intelligent decision in terms of choosing a particular RP process and associated materials depending upon the necessity and the requirements of the end user.

Process tuning/ benchmarked process:

This concerns the iterative process of the benchmarking exercise for standardizing particular processes. A simple DOE and additional case studies can be useful in the parametric optimizations and process tuning of particular processes to evolve with benchmarked procedures. Vital information obtained for particular processes will be updated in a saturated database as process benchmarks.

Part of the proposed approach begins with the design of benchmark parts that will be used in testing the capabilities of processes/systems and simultaneously identifying the process benchmarks. Details on the proposed benchmark part, and details of its fabrication on the various RP processes like the SLA, SLS, FDM and LOM can be referred from Wong [2]. Some of the problems encountered during the fabrication of the benchmark part are also discussed.

Conclusion

A generalized approach for an integrated benchmarking process plan is highlighted so that efficient standardizations can be done for the entire RP processing. The proposed approach could be time consuming but yield more meaningful results. Once the standardizations are set right, a web accessible intelligent decision support system would be able to suggest to a RP user about the information on a system based on a particular process and provide him with relevant information of the most suitable system and process that could help him realize his prototype in the best possible outcome. The benchmarked processes and the measured data that can be obtained by fabricating the standardized benchmark part, and later stored in a saturated database [5] could provide even more useful solutions for the user's needs, in terms of geometric accuracy, surface finish, size, geometrical features, etc.

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