



HAL
open science

Manufacturability Analysis System: Review, Issues and Future Trends

Syaimak Abdul Shukor, D Axinte

► **To cite this version:**

Syaimak Abdul Shukor, D Axinte. Manufacturability Analysis System: Review, Issues and Future Trends. International Journal of Production Research, 2008, 47 (05), pp.1369-1390. 10.1080/00207540701589398 . hal-00513001

HAL Id: hal-00513001

<https://hal.science/hal-00513001>

Submitted on 1 Sep 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Manufacturability Analysis System: Review, Issues and Future Trends

Journal:	<i>International Journal of Production Research</i>
Manuscript ID:	TPRS-2007-IJPR-0186
Manuscript Type:	State-of-the-Art Review
Date Submitted by the Author:	12-Mar-2007
Complete List of Authors:	Abdul Shukor, Syaimak; University of Nottingham Axinte, D; The University of Nottingham, Dept of Man Engineering and Ops Mgmt
Keywords:	DESIGN FOR MANUFACTURE, EXPERT SYSTEMS
Keywords (user):	Manufacturability Analysis System(MAS), Expert System in MAS



Manufacturability Analysis System: Issues and Future Trends

S. A. SHUKOR*, D. A. AXINTE

School of Mechanical, Materials and Manufacturing Engineering,

University of Nottingham, UK.

Traditionally, design and manufacturing activities have taken place sequentially rather than simultaneously leading to inefficient and time consuming iterations between design and manufacturing stages. In order to expedite these iterations, Manufacturability Analysis Systems (MAS) have been developed to allow the evaluation of various manufacturability aspects during the design stage and consequently to reduce the costs and time to market of the designed products. The definition, concepts, advantages of MAS and its current state of development and applicability in the industrial environment are discussed in the introduction of the paper. Then, key issues and technologies related to the construction of MAS such as methodologies applied in data input mechanisms, techniques for manufacturability reasoning and formats of the outputs generated by MASs are analysed. Furthermore, applicability of MAS to various manufacturing processes and aspects such as manufacturability and fixturability indices that can be analysed and produced through MAS are also commented. Disadvantages and limitations emerged from utilisation of MASs are critically analysed and presented. Finally, the paper concludes with discussion and suggestions for some prospective research trends and challenges in building and exploiting MAS. Particular attention is paid to the application of MAS to micro-manufacturing processes on which,

* School of Mechanical, Materials and Manufacturing Engineering, University Park, University of Nottingham, NG7 2RD, Nottingham, UK. Email: epxsa7@nottingham.ac.uk

1
2
3 nowadays, both academics and industry are focusing their attentions for identifying future research and
4 technological challenges and opportunities.
5
6
7
8
9

10
11 *Keywords: Manufacturability Analysis System; Manufacturability assessment and reasoning; Expert System in MAS.*
12
13

18 **1. Manufacturability Analysis System (MAS)**

21 **1.1 Introduction**

24
25 Traditionally, the translation of a conceptual design into a final product has been accomplished by
26 repetitive iterations between design and manufacturing stages of the product development life cycle.
27 Concepts generated in the design stage are passed to the manufacturing stage for the engineers to check on
28 any manufacturing-related problems. If manufacturing engineers encounter significant fabrication
29 difficulties, the designs are passed back to the design department for appropriate modifications. Designers
30 might be unaware of specific manufacturing details or rules, which sometimes result in 'non-
31 manufacturable' designs or require unreasonable increase of fabrication costs. This is the main reason of
32 the time-consuming iterations occurring between the designs and manufacturing stages.
33
34
35
36
37
38
39
40
41
42

43 According to Gupta et. al (1997), in order to expedite or minimise the number of these iterations,
44 Manufacturability Analysis Systems (MASs) has been developed to allow manufacturability aspects to be
45 analysed during the design stage and thus to enable a 'smooth' transition between the design and
46 manufacturing stage. When the number of the iterations are lessen, the time taken to bring the product to
47 the market is shortened and consequently that enables the reduction of manufacturing costs of the designs
48 (Boothroyd 1994; Rao 1999). Thus, more efficient product development techniques will stimulate faster
49 promotion of new concepts and products into the market at lower costs and reduced number of iterations;
50 this leads to improved competitiveness of manufacturing companies (Rao 1994).
51
52
53
54
55
56
57
58
59
60

1.2 Definition

Manufacturability is one of the key aspects in product development life cycle that has to be assessed and analysed at the design stage. In order to do so, the designer needs to have access to knowledge and information about the manufacturing environment which facilitates the decision making activities. Gupta et. al (1997) highlighted that MAS are one of the modern tools that have been developed to meet the purpose of the concept *design right at the first time*. With the current needs of a tool that is able to evaluate the manufacturability aspects at the design stage, it is becoming increasingly difficult to ignore the role played by MAS in the product development life cycle. This concept ensures that the 'ready for manufacture' designs are exempted or at least reduced from the iterations previously discussed. MAS can be implemented to reduce the time taken to generate a product by virtually checking its manufacturability. Rao (1994) defined manufacturability as the ability to reproduce a given part with minimal waste, such that it satisfies the requirements in intended use, while meeting the business goal. With the development of CAD, CAM and the introduction of Concurrent Engineering (CE) concept in product development, manufacturability becomes a key element of CAD/CAM systems. The main objective of the current efforts into this field is to develop a tool for computer aided Design for Manufacture (DFM) that can be used during early design stages to improve product quality from the manufacturing point of view (Gupta 1995). It is envisaged that MAS will enable the analysis of both manufacturability and functionality aspects such as tolerances, surface finish, dimension, machining strategies related to material properties and part geometrical specifications; all considered at the early stages of product development with direct implications on the reduction of lead times taken of the product to the market.

1.3 Advantages of MAS

The assessment of manufacturability aspects of the proposed designs not only acts as a supportive tool to generate designs with the correct measures but it also provides other integral components related such as redesign suggestions, material and process selection, process sequencing and set-up of process planning. The implementation of MAS in the design stage is believed to give positive impact to the product development life-cycle as a whole. The main advantages offered by the use of MAS originated from the recent published literature are as follow:

- During the manufacturability analysis, users can be supported with suggestions for critical changes of the designs to enable their manufacture. These redesign suggestions are based on rules embedded in the Knowledge-Based (KB) of the Expert System (ES) leading towards the reduction of iterations between design and manufacturing stages. Thus, redesign suggestions represent the major outputs of MASs as it enhances the quality of single/interrelated part designs.
- Provides intelligent assistance in selecting suitable processes and materials based on the compatibility of the proposed designs and built-in knowledge on materials and processes, rules and constraints related to them.
- Assists in determining suitable process sequences for fabricating the proposed designs; this can be done based on feature and manufacturing interactions, production cost and time criteria for the purpose of production optimisation.
- Assists designers lacking in-depth knowledge of the related manufacturing process while enabling the utilisation of expert information for design assessment.

- Represents a key step in incorporating manufacturing issues during design stage to shorten product development time, reduce the number of iteration between design and manufacturing stages, minimises development costs, reduce rework and ensure a smooth transition of designs into production.

Currently the implementations of MASs are being used to analyse designs' manufacturability aspects by generating outputs such as redesign suggestion, process planning, material and process selection and others. Examples of MAS implementation can cover a wide range of applications: from shipbuilding projects, where MAS supports automated virtual assembly of parts/sub-assemblies (Sanchez 1997) , designing an improved version of golf club heads (Chen 2001), assist product designers, process planners and die designers working in small and medium sheet metal industries for assessing manufacturability of sheet metal parts (Kumar 2006) and as a material advisor in providing the selection of suitable material in powder metallurgy process for fabricating moulds (Smith 1999; Cherian 2001). Within the broader context of modern design and manufacturing digitisation, the steps made towards the unification of concepts into intelligent and industrially usable MAS is regarded as a strategic step towards next fully integrated and automated production systems.

1.4 Scope of the paper

The paper reviews and discusses issues related to MASs, advantages and limitations of MAS as well as their future challenges and directions of development. In the first part, the paper makes a brief discussion on MASs' key issues such as methodologies for their construction including input mechanisms, analysis of manufacturability aspects and system outputs followed by highlights on the applicability of MAS to various manufacturing processes. Next, challenges and limitations faced by the current MAS

1
2
3 approaches are commented in relation to their structure, option of system outputs and techniques in
4
5 analysing manufacturability aspects. The final part of the paper gives a brief summary and discusses the
6
7 prospective research trends and future challenges on MAS development.
8
9

10 11 12 13 **2. Key Issues in MAS**

14
15
16
17 In this section, the discussion is on the methodologies and approaches of MAS construction, output
18
19 generation and its applicability.
20
21

22 23 24 **2.1 Approach and methodologies of MAS construction**

25
26
27
28 MAS have been developed using different combination of approaches, technologies, software and
29
30 tools. The result of this study indicated that most MAS have been constructed based on a three-steps
31
32 unidirectional flowchart methodology that includes data input mechanisms, engines for manufacturability
33
34 aspects analysis and reasoning and outputs reporting. Figure 1 shows the flowchart of MAS construction.
35
36
37

38
39
40 Figure 1: Basic methodology of MAS development
41
42
43

44
45 The first step to be considered in constructing MAS is the data input mechanism where all required
46
47 design data and manufacturing information are fed into the system. As example, properties of the proposed
48
49 design such as dimension and tolerance are being input into the system. The next step in this methodology
50
51 is to analyse the input gathered for part manufacturability assessment. This is the most important step in
52
53 MAS as it determines the accuracy of manufacturability outputs. All input data are analysed according to
54
55 the manufacturability constraints to determine the level of difficulty in manufacturing the proposed design.
56
57
58 The final component in this methodology is generating outputs to reflect the assessment and evaluation of
59
60

1
2
3 manufacturability aspects of the proposed designs and to interactively assist designers in considering
4
5 manufacturing aspects during the design stage.
6
7
8
9

10 11 *2.1.1 Data input mechanisms* 12 13 14 15

16 The current study found that there are three mechanisms that have been implemented in MASs for
17
18 inputting data into the system: obtaining data from CAD model, using user-system interactions and
19
20 collection of manufacturing information. The type of data extracted or collected from the input
21
22 mechanisms consist of geometrical, material and technological properties of the 'to be analysed' part such
23
24 as: dimensional, geometrical, tolerance and surface finish specifications, material chemistry and
25
26 mechanical properties, production rates and quality control measures.
27
28
29

30 From the published literature, it can be concluded that there are various techniques that can be used
31
32 in obtaining data from CAD model such as: feature-based extraction system; neutral files usage such as
33
34 STEP, IGES and STL. Additionally, data extraction can also be performed via the algorithm embedded
35
36 into the CAD system such as using Auto LISP (Kumar 2006) and CADKEY (Lee 1997). Geometric
37
38 reasoning technique has also been implemented in order to extract part definition from CAD model (Chen
39
40 1995; Dissinger 1996; Jacob 2004). Other techniques developed are 3D recognition model based on the
41
42 design specifications of CAD model (Lu 1996; Horvath 1999; Chen 2001; Howard 2006), attribute
43
44 extractor (Tharakan 2003), CAD modeller (Gebresenbet 2002) and data extraction from process simulation
45
46 (Giachetti 2001; Giachetti 2005). The data obtained from a CAD model interprets the design details such
47
48 as geometrical specifications and feeds the needed information to the system. Geometrical specifications
49
50 such as features, shapes, dimensions and technological requirements such as tolerances, surface finish are
51
52 some of the essential parameters extracted from a CAD model which considered as main input parameters
53
54 into MAS.
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Another type of input mechanism is based on user-system interaction where the system prompts the user with questions leading towards the collection of information necessary to perform part manufacturability analysis (Venkatachalam 1993; Myint 1998; Zha 2003; Giachetti 2005; Giannakakis 2006; Kumar 2006). Usual questions are related to workpiece material, part dimensional and geometrical specifications (Venkatachalam 1993; Myint 1998; Zha 2003; Giachetti 2005; Giannakakis 2006; Kumar 2006), processing techniques (Kumar 2006), and technological/functional properties of the component object such as geometric volume, production volume, expected surface finish, dimensional tolerance, critical surfaces (e.g. minimum wall thickness) (Venkatachalam 1993). As example, during a consultation session, users input the needed data in the provided interface that once being sufficient, the programs starts to analyse them based on the rules embedded in KB (Kumar 2006). In this system, important data and information related to fabricating a sheet metal component such as type of material, sheet thickness, minimum corner radius sheet metal part, minimum width of slots along blank profile, shapes and dimensions of holes on the part and maximum dimension (length/width) of component are being gathered from user-system interaction mechanism for the purpose of manufacturability assessment (Kumar 2006).

The last input mechanism is the collection of manufacturing information that is embedded into MAS. Data related to manufacturing process, materials and machining tools are available for the user to select during the data input step (Krishnan 1997; Myint 1998; Giachetti 2005). In this mechanism, users are allowed to choose related data and parameters from the collection of manufacturing information embedded in the system. The difference clearly owned by this mechanism compared to the previous one is all information are readily embedded, and users only have to choose them appropriately, while in the previous mechanism, users are required to input all needed data through the interface during the interaction.

From the above discussion, it can be concluded that most of the developed MASs used feature-extraction system to obtain related data from CAD model. Research in this field is rapidly developing to find ways and approaches for accurately extracting design details from the features. One major drawback

1
2
3 of this approach is difficulty in appropriately recognising and interpreting the relationship between
4 intersecting features on the analysed part (Gupta 1995; Hayes 1996; Gupta 1997; Jacquel 2000; Chen
5
6
7
8 2003; Korosec 2005; Nasr 2007). Other limitations originate from loss design intent and incompleteness of
9
10 design and manufacturing information (Chen 2003; Nasr 2007). The other two mechanisms, user-system
11
12 interaction and collection of manufacturing information, are not yet widely used as it involve input
13
14 activities from user and then additional effort for gauging/interpreting their applicability in other
15
16 manufacturing environments. Nevertheless, these two mechanisms are also given significant attention in
17
18 the research community as it could offer the advantage of providing more accurate input information into
19
20 MAS. This is because the input mechanism gets data directly from designer (user-system interaction) and
21
22 from related manufacturing process constraints.
23
24
25
26
27
28
29
30
31
32

33 *2.1.2 Approaches in analysing manufacturability aspects*

34
35
36

37 The next step in this methodology is to analyse the gathered input. This is the most important step
38
39 in MAS as it determines the output measures on which part manufacturability is assessed. Most of the
40
41 developed MAS employed ES techniques to analyse design manufacturability aspects. ES is a computer
42
43 application system that employs Artificial Intelligence (AI) in solving problems in a specific domain. ES
44
45 can provide a relatively inexperienced user with a comprehensible assessment of a problem where an
46
47 expert is unavailable. This review focuses on the implementation of ES techniques in assisting the
48
49 analysing of the manufacturability aspects.
50
51
52
53
54
55

56 *2.1.2.1 Expert Systems in MAS*

57
58
59
60

1
2
3 Recent studies show that general manufacturability aspects can be analysed automatically using
4 various ES approaches especially at the design stages of the product realisation. The assessment of
5 manufacturability aspects are done by using various approaches such as: Neural Network (NN), Fuzzy
6 Logic (FL), Agent-Based System (ABS), Rule-Based System (RBS), Object Oriented Technique (OOT),
7 Analytical Hierarchy Process (AHP) and Case-Based Reasoning (CBR). Manufacturing rules such as
8 processes/materials constraints and properties which are obtained from experts, handbooks, catalogues,
9 experiences and brochures are embedded in the system to be used as guide for assessing the
10 manufacturability of the design. The analysis is made based on rules of manufacturing processes, usual
11 practice of fabrication of specific features or designs, materials/ processes constraints and production cost
12 and time.
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

29 A. Approach of Expert System modelling 30 31 32 33

34 Literature survey on the implementation of ES in developing MAS identified various combinations
35 of specific AI techniques. Statistically analysing the techniques used for building ES; it seems that
36 among the most popular approaches (approx. 40%) used RBS (Scherer 1996; Myint 1998; Smith 1999;
37 Arezoo 2000; Brissaud 2000; Chan 2003; Zha 2003; Jacob 2004; Korosec 2005; Giannakakis 2006;
38 Howard 2006; Kumar 2006; Ramana 2006). RBSs use IF-THEN clauses with logical combinations to
39 represent its knowledge base. According to Kusiak and Chen (1998), RBS is being frequently applied
40 because the IF-THEN rules are easily acceptable as they are similar to common sense logic and the
41 familiarisation with logic based languages such as LISP and Prolog. For example, the IF-THEN rules
42 related to fabrication sheet metal parts are structured in the KB; then, the system interactively searches
43 the list of rules in order to determine which rules are satisfied with the given input (Kumar 2006).
44
45
46
47
48
49
50
51
52
53
54
55
56

57 On the other hand, approximately 23% of the researches used OOT in developing the MAS (Chen
58 1995; Amalnik 1996; Amalnik 1998; Gupta 1998; Horvath 1999; Jacquel 2000; Giachetti 2001). OOTs
59
60

1
2
3 represent the solution in the form of program that contains model entities, where each model can be
4 represented by an object. For each object defining the model, it contains data and programming codes
5 that can be performed on those data. In the development of MAS, OOT offers a way of representing
6 objects that are reasoned about, properties and relationships between them. Each of the subclasses of
7 objects has other subclasses related to them and the relationships occurred between them are clearly
8 defined. Using OOT approach, the analysis is based on the objects and the relations between its sub-
9 classes. For example, electrochemical machining is defined as the main object in the manufacturability
10 model and its machining criteria such as workpiece material, electrolyte solution, tool electrode,
11 geometric feature and electrochemical machine are defined as the subclasses (Amalnik 1996; Hayes
12 1996; Amalnik 1998). This approach has been used for analysing the manufacturability aspects by
13 considering the relationships occurred between the design features and the subclasses stated above.
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

29 Another approach used to build ES is AHP which amounts up to 10% of the published researches.
30 The AHP is a mathematical based decision making technique that allows both qualitative and
31 quantitative aspects to be taken into account when making decisions (Ong 2000; Ong 2003). It not only
32 helps the decision makers to choose the best alternative, but also provides a clear rationale for the
33 choice of AHP by developing and assigning priorities of criteria to judge them (Saaty 2001). AHP
34 allows the use of weighting factors to reflect their functional importance (Ong 2003) or to determine
35 the relative weight (Ong 2000) for each attribute involved in the estimation of the manufacturability
36 index. Manufacturability index is a useful indicator to reflect the relative ease of manufacturing
37 parts/features while expressing associated manufacturing difficulties. AHP is implemented to assign
38 weighting factors to features in order to indicate their functional importance as different features have
39 different roles in supporting the functional requirements of the part (Ong 1996; Ong 2000; Ong 2003).
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54

55 Another approach in modelling ES is called Hybrid Approach (HA) which the assessment is done
56 by combination of different approaches. Among the implemented HA could be specified as following:
57 RBS and FL (Jiang 2003); OOT and RBS (Venkatachalam 1993; Marquez 2001; Ramana 2005);
58
59
60

1
2
3 Frame-based and RBS (Yuyin 1996); NN, FL and RBS (Ravinwongse 1997); combinations of ABS,
4
5 OOT and RBS (Jia 2004); and FL and NN(Gu 1997). As example, in a MAS developed by Cherian et
6
7 al. (2001), HA is implemented by combining RBS, Bayesian NN and heuristics for assessing the
8
9 manufacturability aspects. RBS is implemented to evaluate the design geometry while Bayesian NN
10
11 and heuristics are used to evaluate the material and process parameter selection. Heuristic here is
12
13 defined as the knowledge of good practice, good judgment, and plausible reasoning in the field of
14
15 material and process combination. In this study, the overall usage of HA accounted nearly 16% of the
16
17 reported approaches of ES in developing MAS.
18
19
20
21

22 Other approaches being implemented accounting for 6% of the research approaches are NN
23
24 (Korosec 2005) and ABS (Shiau 2000; Shiau 2001; Medani 2005; Medani 2006). NN in ES
25
26 applications consists of many nonlinear computational elements which form the network nodes and
27
28 linked by weighted interconnections (Hopgood 1993). It is defined as an interconnected group of
29
30 artificial neurons (nodes or units) that uses mathematical or computational models for data processing
31
32 based on process of adaptation/learning from a set of training patterns. This shows that NN is an
33
34 adaptive system which changes its structure based on external or internal information flowing through
35
36 the network (Gurney 1997). They are usually employed to model any nonlinear mapping between
37
38 variables and usually used in classification tasks. Korosec et al. (2005) used NN to simultaneously
39
40 evaluate the features complexity in a CAD model with manufacturing capability. In this work, the
41
42 relationship between surface finish, surface hardness and part manufacturability are expressed as a
43
44 matrix, which shows a very strong non-linear correlation between the parameters mentioned. Here, NN
45
46 is capable to analyse the non-linear correlation by sufficient training using calibrated examples while
47
48 being able to acquire new knowledge from practice.
49
50
51
52
53

54 For ABS, the agent's functionality is defined by the specific needs for the integration of the
55
56 decision-making steps into a common manufacturing decision-making environment. As example
57
58 (Medani 2005; Medani 2006), the manufacturability assessment is based on several distributed
59
60

1
2
3 cooperating agents supporting the design, manufacturing and facility assignment activities. Each agent
4
5 (design agent, manufacturing agent and facility agent) is related and acts as a decision maker according
6
7 to its activities.
8
9

10 Figure 2 shows an estimative distribution of the 'popularity' of the approaches implemented in
11
12 modelling ES for MAS. From the timeline perspective, RBS, OOT and HA have been implemented
13
14 since 1996 and are still being employed in developing MAS while the most recent techniques, NN,
15
16 ABS, and AHP are fast expanding.
17
18
19
20
21

22 Figure 2: Type of approach used for modelling ES fro MAS
23
24
25

26 B. Tools to develop Expert System 27 28 29 30

31 There are many types of tool, software packages and programming languages available in the
32
33 market for developing MAS using ES. According to Hopgood (1993), there are four types of tools
34
35 available in assisting user to construct ES as follows:
36
37
38
39

- 40 • ES shells
41

42 It is a complete ES that includes an Inference Engine (IE), a user interface for programming
43
44 and for running the system but it does not provide the KB. Users are required to develop the
45
46 KB by entering the rules into the system while no supervision is required for the development
47
48 of IE. Such an approach is easy to use and allows the construction of simple ES; however, the
49
50 major drawback is the inflexibility in supporting knowledge representation.
51
52
53
54
55

- 56 • Toolkits
57

58 They offer almost complete facilities to develop ES such as the features of ES shells, object-
59
60 oriented programming and AI languages. However, the following main drawbacks of the

1
2
3 toolkits can be specified: need of powerful processor, large amounts of disk space and memory
4 (RAM); costly license fees; 'embedded knowledge' with reduced flexibility for customisation.
5
6 Among the toolkits available are KEE, ART and Goldworks. Currently, there are some toolkits
7
8 available in the market that has been built using non AI languages such as C or C++ (Pro
9
10 Kappa and Nexpert).
11
12
13
14

- 15
16
17
18 • Programming languages for AI

19
20 A programming language is generated specifically to cater the development of various AI
21
22 applications. Two important features of AI languages are the ability to manipulate symbolic
23
24 data such as characters, words and numbers and to provide an interactive programming
25
26 environment. Programming languages that focus totally on AI applications such as LISP and
27
28 Prolog, offer increased flexibility compared to the above tools.
29
30
31
32

- 33
34 • Conventional programming languages

35
36 Programming languages such as C, Pascal and FORTRAN are used as tools for developing the
37
38 ES. These types of tools require more complicated and tedious program routines compared to
39
40 the above mentioned tools. Even though it requires complicated programs, they offer the most
41
42 flexibility in developing AI program.
43
44
45
46
47

48
49 The distribution of tools usage in developing the ES for MAS based on the four types of tools
50
51 discussed above is concluded as shown in Table 1 below.
52
53
54

55
56
57
58
59
60
Table 1: Distribution of ES tools

Figure 3 shows an estimation of the percentage distribution of tools used in developing ES for MAS. The study on the published literature shows that approximately 43% of the developed MAS

1
2
3 used conventional programming language, 33% implemented the AI Languages, 19% used
4
5 Toolkits to develop MAS and only 5% used ES shells.
6
7
8
9

10 Figure 3: Distribution of tools used in developing ES
11
12
13
14

15 *2.1.3 Outputs generated from MAS assessment*

16
17
18
19

20 The final component of MAS generates the outputs as an evaluation of manufacturability aspects such
21 as: redesign suggestions; selection of processes and materials; process sequencing setups; estimation of
22 production costs and times; process planning setups. The main objective of MAS is to analyse and
23 evaluate the proposed design based on manufacturability aspects in determining whether the design can be
24 manufactured or which are the necessary changes on the design to enable its materialisation into a real
25 part. Thus the results of MAS can take the following forms.
26
27
28
29
30
31
32
33
34
35

36 A. Redesign suggestion

37
38
39
40

41 During the manufacturability analysis, the users are prompted with suggestions for changes of the part
42 design in order to ensure its manufacturability. The redesign suggestions are usually made after the
43 design has been analysed on the manufacturability aspects, i.e. ES has been run entirely, or during the
44 input session of the design data. The redesigns suggestions are based on the rules embedded in the KB
45 and are directed to assist designers lacking manufacturability knowledge and thus enabling the
46 reduction of technical iterations between designs and manufacturing stages. Approximately 56% of the
47 surveyed MASs provide redesign suggestions as the MAS outputs. It can be concluded that redesign
48 suggestion is one of the major outputs of MAS that can assist designing products correctly with the
49 helps of manufacturing information available at the design stage.
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8 B. Provide selection of processes and materials
9
10

11
12 MAS can also provide assistance in selecting suitable combinations of processes and materials for the
13 proposed design based on process knowledge and rules. MAS supporting material selection have been
14 reported in relation to the following manufacturing processes:
15
16
17
18

- 19
20
21
22 • Machining such as milling (Venkatachalam 1993; Tharakan 2003), drilling (Venkatachalam
23 1993), electrochemical machining (Amalnik 1996), grinding (Jacob 2004), turning (Arezoo
24 2000), solid free-form fabrication process (e.g. stereolithography and selective laser sintering)
25 (Gupta 2003); various conventional machining processes for metallic components fabrication
26 such as milling, drilling, boring, grinding and broaching (Chan 2003).
27
28
- 29 • Forming and shaping such as injection moulding (Marquez 2001; Tharakan 2003), powder
30 metallurgy (Smith 1999), forging (Medani 2006).
31
32
- 33 • Casting: die casting, sand casting (Medani 2006).
34
35
- 36 • Other: LIGA process(Scherer 1996); various manufacturing processes that involved in
37 fabricating MEMS devices such as plastic injection moulding, forging, sheet metal forming,
38 extrusion, micro-milling, die casting, shell mould casting, investment casting and
39 electrodischarge machining (Zha 2003).
40
41
42
43
44
45
46
47
48
49
50
51
52

53 Usually the material selection is based on the compatibility of the particular groups of materials with
54 types of manufacturing processes such as those stated before. It can be concluded that MAS have been
55 mainly developed for particular processing techniques. This is somehow expected since the
56
57
58
59
60

1
2
3 relationships between processing techniques and workpiece material have reduced transferability to
4 other processes/environments.
5
6
7
8
9

10 C. Process Sequencing

11
12 As reported, MAS can also identify/propose suitable process sequences in fabricating the proposed
13 design. The system matches the manufacturing process requirements against existing machine
14 capabilities and availabilities while seeking the reduction of production cost and times. The selection
15 of process sequences are based on the related factors such as process type and capabilities, process
16 sequence applicability and relationship between features of the analysed part. Thus, process
17 sequencing can be suggested based on the analysis of manufacturability aspects of the design while
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

31 D. Other outputs

32
33 Additionally, MASs are capable to produce other outputs such as estimation of production cost and
34 time, process planning setup and tooling approaches/orientations. The estimation of production cost
35 and time is generated using mathematical models based on the results of the analysis of the optimised
36 manufacturing processes. As example, cost estimation has been developed for die casting based on the
37 mathematical modelling used in the industry practice for this process with input in form of design and
38 process parameters (Venkatachalam 1993). While parameters such as air-travel, cutting length, feeds
39 and hourly rate were adapted in cost estimation module for calculating the value for milling process
40 (Tharakan 2003). Moreover, process planning setup was generated based on the optimised geometrical
41 and technological properties of the design related to process plan guidelines for specific manufacturing
42 processes. Additionally, by manipulating information relating to part geometry and specific tools
43 libraries, MAS is reported to be capable of providing optimised tooling orientation (Dissinger 1996;
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60 Yang 1999).

2.2 Applicability of MAS to various manufacturing processes

Usually, the development of MASs is related to particular categories of manufacturing processes such as: casting, forming/shaping and machining. An overview of the implementation of MAS into various categories of manufacturing processes adapted from Kalpakjian et al. (2000) is presented in Table 2.

Table 2: Categories of manufacturing processes implemented with MAS

Beside the manufacturing processes highlighted in the Table 2, there have been reports on MASs that are capable on dealing with various manufacturing processes although no specific processes are particularly mentioned. Most of the reported manufacturing processes in the current study of MAS development mentioned on processes that cater the fabrication for macro size product while less attention is given to MAS applicability to micro size products. From the above list of manufacturing processes, it can be concluded that the research in manufacturability assessment can be divided into two broad areas: macro and micro manufacturing process.

Rough statistical analysis of published work shows that approximately 92% (Figure 4) of the researches are focusing on applicability of MAS to macro-manufacturing processes. Only 8% are targeting the micro-manufacturing processes such as fabrication of MEMS devices (Zha 2003; Li 2006) and LIGA process (Scherer 1996). As example, a system that is able to select the 'best combination' of material and process in a concurrent environment for fabricating MEMS devices based on proposed design and constraints imposed from the material and process selected is claimed to be developed by Zha and Du (2003). The proposed micro-structures design is dynamically checked by an inference machine supported by rules related to LIGA process that are embedded in KB (Scherer 1996). In this line, it can be concluded that the major differences between the MAS in macro and micro-manufacturing process lies in the content of the KB developed. Due to increase demands of micro-product in the current market, the applicability of

MAS in this field has a big research potential that needs to be explored as it assists in fabricating a high quality micro-products.

Figure 4: Distribution of MAS applicability towards two areas of manufacturing process

2.3 Other aspects that can be analyzed through MAS

MAS can also provide users with indices/indicators to enable the comparison between available processes reflecting the ease of machining unitary/combined features of the analysed part. The manufacturability indices are generated based on geometrical (orientation, intricacy, accessibility, dimensional), technological (workpiece surface finish, part tolerance, employed processing method) (Ong 1996; Ravinwongse 1997; Myint 1998; Ong 2000; Gebresenbet 2002; Ong 2003) and assembly (part relationships, type and behaviour of assembly such as how the mating between features take place in the assembly) indices (Gebresenbet 2002). An index for each feature of a component with respect to each attribute stated above is obtained using parametric fuzzy membership technique (Ong 1996; Ravinwongse 1997; Ong 2000; Gebresenbet 2002; Ong 2003). Manufacturability indices generated by Yannaoulakis (1991) are calculated based on the estimated manufacturing times for each feature of a part and then they are used to rank the manufacturing sequences to be employed for the features. The overall manufacturability index is determined from the summation of the indices of the attributes and multiplied by their respective weight factors (Ong 1996; Ravinwongse 1997; Ong 2000; Gebresenbet 2002; Ong 2003). Gupta et. al (1998) also mentioned the development of manufacturability rating to reflect the ease or difficulty of which design can be manufactured but there are no details explanation given. It can be concluded from the current published literature that the assessment of the manufacturability indices are based on the cost and time aspects in order to manufacture the design.

Another important aspect being analysed in MAS is fixturability; where surfaces are rated for fixturing purposes based on related attributes. Fixturability Index (FI) is generated from the summation of

1
2
3 the indices from various related attributes such as: surface finish, relation between features, geometrical
4 complexity of surfaces, symmetrical properties, percentage area of the face left unmachined, and
5
6 orientation of a face with respect to tool direction. The current research suggested that only planar surfaces
7
8 of the features were considered for fixturability assessment because it provides easy fixturing set-up (Ong
9
10 1996; Ong 2000). Fuzzy-set based match functions were used to analyse the fixturability aspects based on
11
12 the attributes mentioned above while FI indicates the suitability of a planar surface for fixturing purposes.
13
14
15
16
17
18
19
20

21 **3. Problems and Limitations in Current MAS**

22
23
24 The development and implementation of MAS in the design-manufacturing stage has been
25 progressed rapidly over the last decades. From the advantages and applications discussed above, it shows
26 that MAS has a promising future to be implemented in various manufacturing fields especially in assisting
27
28 designers and manufacturing engineers to minimise the numbers of iterations between corresponding
29
30 stages of the production routes. Beside all the advantages and its promising future, there are still
31
32 limitations and challenges occurred in the current MAS.
33
34
35
36
37
38
39
40

- 41 • The applicability of MASs is restricted to single manufacturing process

42
43 Even though MASs have been applied to various types of manufacturing processes, most of the current
44 systems provide assessment to cater only single type of manufacturing process. This means that the
45 analysis of manufacturability aspects is done based on that single manufacturing process while the
46 opportunity to take into account the successions, interactions or options of other process are not
47
48 considered. Significant limitations lie in the fact that less option of manufacturing processes available
49
50 in the system reduces the flexibility in assessing the manufacturability aspects. Besides that, the
51 applicability of MASs is also limited to macro-manufacturing domain and less attention is given to the
52
53 new emerging processes such as micro-manufacturing techniques.
54
55
56
57
58
59
60

- Limited outputs produced by MASs

Despite various outputs that can be produced by MASs, most studies in the field have only focused in providing limited number of outputs combinations. The study shows that approximately 74% of the developed MASs provide only one or two combinations of outputs. Redesign suggestion is the most popular single output provided by developed MASs while the most popular combined outputs are: process and material selections supported by cost/time estimations; redesign suggestion combined with manufacturability index. Limited outputs of MASs can be regarded as inefficient use of technical data base/information built in the system and also the relationship occurred between each of the output discussed above. By choosing to produce limited number of outputs will reduce the effectiveness and also the accuracy of MASs assessments and interactive suggestions.

- Issues in input mechanisms

Most of the developed MAS applied feature-extraction system to gather CAD data as the input to MAS. Limitations in using this approach can arise from: imprecision/fuzziness of extracted data; inflexibility of type of data; difficulty in interpreting relationships between various features of the part. Implementation of the latest approach of feature-extraction system in MAS that can provide a more accurate input mechanism depends on the on-going research in this field. As known, the development of feature-extraction systems is still a stringent research topic targeted to identify ways to collect accurate and self-sufficient data/design details from the features. Thus this can affects the accuracy of the data being input to the system in assessing manufacturability aspects.

- Limited capabilities in analysing manufacturability aspects

Most researches discussed in this paper show limited capabilities by focusing solely on analysing the manufacturability aspects on the proposed design while neglecting other important aspects such as part

1
2
3 functionality. As example, estimating design accuracy using the tolerances are made based on the
4
5 manufacturability aspects only, while its influence on part functionality is totally neglected.
6
7 Dimensional and geometrical tolerances should be employed to specify permissible variations for
8
9 compatibility with the functionality of the proposed design; thus, tolerances are not only design
10
11 specifications but also play an important role in assessing manufacturability and functionality of parts.
12
13 Most MAS reported to date consider only manufacturability aspects while sacrificing the functionality
14
15 aspects in doing their assessment (Gupta 1995; Hayes 1996; Ong 2000; Jacob 2004; Ramana 2006).
16
17 The functionality aspects are usually assessed manually or are totally neglected. The developed system
18
19 were still hit the target of producing the proposed design that fulfil the manufacturability aspects but
20
21 lacking in terms of functionality.
22
23
24
25
26
27
28

29 It can be concluded that even though MASs offer technical advantages in connecting design and
30
31 manufacturing engineering, they still have limitations to be tackled. With their significant implications for
32
33 future practice and industrial exploitation, the limitations highlighted above represent a big potential
34
35 incentive to venture into for further research development and exploration.
36
37
38
39
40
41

42 **4. Prospective Research Trends and Challenges**

43
44
45 While challenging tasks lies ahead, the development of even-move efficient MAS is recognised as a
46
47 crucial linkage element between CAD and CAM. Based on published literature and critical analysis of MAS,
48
49 the following areas of interest can be identified for further research:
50
51
52
53

- 54 • Implementation of Information Technology elements in developing MAS

55
56 The rapid developments in the field of Information Technology (IT) enabled fast-responding and
57
58 intelligent construction of automated MAS. Among the example of IT implementation in MAS
59
60 construction could be specified as following: development of user-system interaction; automatic

1
2
3 feature recognition mechanism in extracting CAD data; usage of application of programming interface
4 (API) methods in CAD data extraction (Lee 1997; Kumar 2006) for MAS input; ES approach in
5
6 assessing the manufacturability aspects assessment; and developments of the outputs display of MAS.
7
8
9
10 Other example mentioned by Gupta et. al (1997), is the development of web-based MAS that can be
11
12 accessed virtually or remotely from anywhere; this approach actively supports the E-Manufacturing
13
14 concept on which, nowadays, more manufactures have started to rely on in running their production
15
16 globalise systems. The implementation of IT is believed to help enhance MAS capability to support
17
18 designers with reduced experience in manufacturing area, increasing the efficiency of design
19
20 refinement according to the manufacturability rules compiled in the generated KB. Additionally, IT
21
22 involvement in MAS construction can enhance the quality of data input mechanisms,
23
24 manufacturability assessment techniques, outputs display and user-system interaction.
25
26
27
28
29
30
31

- 32 • MAS with various outputs

33
34 It is suggested that MAS can produce more combinations of assessment outputs compared to those
35
36 generated by the current systems. Various combinations of outputs can increase the effectiveness of
37
38 MAS as it provides 'enriched' knowledge/recommendations that can assist the end-user system in
39
40 making more comprehensive technical decisions regarding the fabrication of the proposed designs.
41
42 Apart from this, the capability of assessing more robust manufacturability indices/ratings should be
43
44 pursued. It is suggested to consider and combine more related elements such as tolerances, materials,
45
46 dimensions, tooling, tools/parts orientations and process capabilities in determining these indices. It is
47
48 believed that more combinations of related elements would lead to a greater degree of accuracy on the
49
50 generated manufacturability indices. Further research might also explore the possibility of assessing
51
52 functionality aspects of the proposed design. Currently, most of the MAS evaluate the functionality
53
54 aspects manually or are totally neglected. It would be worth considering this aspect during the design
55
56
57
58
59
60

1
2
3 stage as it also plays an important role in determining the function of the design. However, how this is
4
5 to be technically addressed is to be the goal for future research.
6
7
8
9

- 10 • MAS with various applicability of manufacturing processes

11
12 Even though MASs have been applied to various manufacturing processes it can be noted that such
13
14 systems mainly addressed macro-manufacturing processes such as cutting, forming and injection
15
16 moulding, while less attention was paid to micro-manufacturing processes. Micro-engineering deals
17
18 with the development and manufacture of products, whose functional features or at least one
19
20 dimension are at micrometric level (Alting 2003). Micro-products such as sensors, lenses, surgery
21
22 devices, gears, and actuators have become demanded products in industry such as IT, medical and
23
24 biomedical, automotive, telecommunication and electronic industries. The use of micro-products and
25
26 micro-components has been strongly increased through the past five years and the product
27
28 development and design on new micro-products will be the core competence of the companies in
29
30 future(Alting 2003). The increasing demands of micro-products in various industries have geared up
31
32 the development of specific micro-manufacturing processes and technologies. Thus, the needs to bring
33
34 micro-products faster to the market caused the development and the design phases to become more
35
36 challenging tasks. Methods used to design the products with the required quality specifications and can
37
38 be fabricated easily is one of the main issue in designing micro-products.
39
40
41
42
43
44

45
46 In order to design competitive micro-products, which ideally fulfil the required product functions, the
47
48 designers need to develop products that relate to the fast-developing manufacturing details and rules
49
50 (Alberz 2004). Thus, a systematic approach in designing quality micro-products allows the designs to
51
52 be easily manufactured and compatible with the production needs. This means that the designer is able
53
54 to check the micro-manufacturability aspects in their designs before submitting them for fabrication.
55
56
57 From the present study, MASs has been proved to work for macro-manufacturing processes. An
58
59 implication of this is the possibility of the MAS to check micro-manufacturability aspects such as
60

1
2
3 materials used, manufacturing processes involved, acceptable and suitable tolerances and dimensions
4 of micro-products. Further research on implementing MAS in designing and launching micro-products
5
6 is believed to enhance the rapid development of micro-manufacturing techniques. Therefore, there is
7
8 and will be definite need for analysing the micro-manufacturability aspects during the design stage
9
10 products in order to produce accurate and cost-effective micro-products.
11
12

13
14
15
16
17 • MAS with various input mechanisms

18
19 The input mechanism plays an important role in providing data needed for manufacturability analysis.
20
21 In order to feed the system with accurate and relevant data, it is suggested to investigate and develop
22
23 combinations of input mechanisms. This means that besides using only feature-extraction system
24
25 solely for data input, user-system interactions can be implemented together to generate a more
26
27 interactive input session. Another example is the combination of user-system interaction and collection
28
29 of manufacturing information can also be adapted in inputting required data into MAS.
30
31
32
33

34
35
36
37
38 • Source of KB for manufacturing processes

39
40 In most of the developed MAS, the assessment of manufacturability aspects is assisted by database that
41
42 contains manufacturing rules and information for each involved manufacturing process. Measures
43
44 should be taken to upgrade the database to be a KB that allows expert judgement in assessing
45
46 manufacturability aspects for the particular manufacturing process. Further more, the generated KB
47
48 can be applied as source of information for any new development of MAS for that particular
49
50 manufacturing process.
51
52
53

54
55
56
57 • MAS with user friendly features

58
59 Finally, it is suggested that MAS should have user friendly features to ease the usage of MAS so that it
60
meets the purpose of the system in assisting the non-expert users. User friendly refers to the easiness in

operating the system, more interactive feedbacks from the system and the facilities of handling the system.

5. Conclusions

From the discussion made above, it shows clearly that MAS positively contributes towards the design-manufacturing cycle in term of materialising designs with reduced time and cost resources. MAS provides an opportunity for manufacturing aspects to be analysed at the early stages of product development life cycle which helps to reduce problems arising from manufacturing difficulties when they reach production stages. The result of this study can be concluded as follows:

- The main input required by MAS are the CAD details of the proposed design such as: dimensional/geometrical tolerance, surface finish, features relationships and related manufacturing information (manufacturing constraints, process capabilities/compatibilities, materials and part features).
- Expert judgement and feedback given back to user of MAS can be made by analysing the CAD data and manufacturing information concurrently with the support of ES as the inference engine. Manufacturing information such as processes and materials properties can be obtained from experts, handbooks, catalogues, experiences, factory standards and brochures.
- Various outputs can be obtained from manufacturability analysis such as: redesign suggestions or design advisory, selection of materials and processes, process sequencing, process planning setups, estimation of production cost and time, tooling strategies/orientations and manufacturability indices. Many MASs provide limited number of outputs combinations that might lead in obtaining reduced effectiveness/accuracy of MASs. This indicates a need to develop MASs capable to provide more combinations of outputs as technical databases/information built in system will be efficiently used.

- 1
2
3
4 • The future development of MAS is derived by the rapid progress of IT that will leads towards the
5 development of input mechanisms, more efficient approaches for analysis of manufacturability aspects
6 and more interactive format of outputs.
7
8
- 9
10 • The development of MAS can improve the interaction between CAD and CAM facilitating the
11 materialisation of CE concept for the micro-manufacturing process domain. Thus, the main objective
12 in developing MAS could be the evaluation of manufacturability aspects in the proposed micro-design
13 taking into consideration the specifics of these micro-processing technologies. As MAS provides a
14 systematic approach in designing quality micro-products this will allow the proposed design to be
15 easily manufactured.
16
17
- 18 • There is a potential research to be explored for proposing new framework in combining data input
19 mechanisms, manufacturability assessments/reasoning, tools, technologies and types of outputs. As
20 example, for the data input mechanisms, the combination of user-system interaction and the collection
21 of manufacturing information can be adapted as inputs into MAS. Another significant research topic is
22 the new combination of approaches in HA for manufacturability assessment and reasoning. Most of
23 the developed MAS opted for a single approach such as RBS, OOT or NN while HA is believed to
24 provide more flexibility in assessing the manufacturability aspects.
25
26
- 27 • Manufacturability assessment in most MASs is based on database that contains manufacturing rules
28 and information for particular manufacturing processes. It has been suggested to develop KB leading
29 to replace the database that is usually used in previous MASs. The KB generated can be applied as the
30 source of information for manufacturability assessment that can provide expert judgement for any new
31 MAS development.
32
33
- 34 • So far, there have been little discussions about the consideration of part functionality in the assessment
35 of the proposed design. In addition, it is a realistic approach to consider functionality as an element of
36 the manufacturing assessment by giving attention to the dimensional tolerances of the proposed design.
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Despite the rapid development of MAS, there are still significant challenges to be addressed and facilities to be developed for further enhancement of MAS capabilities. Aspects such as applicability of MAS to various manufacturing process, outputs produced, input mechanisms are among the key aspects to look at in the future development of MAS. It is envisaged that MAS will become one of the important components of CAD/CAM systems that allow concurrent communication between CAD and CAM system become more efficient.

Acknowledgements

The authors are grateful for the support from University of Nottingham where the research is carried out. Special thanks go to Universiti Kebangsaan Malaysia for providing the main author's scholarship.

References

- Alberz, A., Marz, J., 2004. Restriction of Production Engineering on Microspecific Product Development. *Microsystem Technologies*, 10 (3), 205-210.
- Alting, L., Kimura, F., Hansen, H.N., and Bissacco, G., 2003. Micro Engineering. *Annals of CIRP* 52, 2 635-658.
- Amalnik, M. S., El-Hofy, H.A. and McGeough, J.A., 1998. An Intelligent Knowledge-based System for Wire-Electro-Erosion Dissolution in a Concurrent Engineering Environment. *Journal of Material Processing Technology*, 79 (1-3), 155-162.
- Amalnik, M. S., McGeough, J.A., 1996. Intelligent Concurrent Manufacturability Evaluation Design for Electrochemical Machining. *Journal of Material Processing Technology*, 61 (1-2), 130 -139.
- Arezoo, B., Ridgway, K. and Al-Ahmari, A.M.A., 2000. Selection of Cutting Tools and Conditions of Machining Operations using an Expert System. *Computers in Industry*, 42 (1), 43-58.

- 1
2
3 Boothroyd, G., Dewhurst, P. and Knight, W., 1994. *Product Design for Manufacture and Assembly*. New
4
5 York: Marcel Dekker Inc.
6
7
8 Brissaud, D., Tichkiewitch, S. , 2000. Innovation and Manufacturability Analysis in an Integrated Design
9
10 Context. *Computers in Industry* 43 (2), 111-121.
11
12
13 Chan, D. S. K., 2003. Expert System for Product Manufacturability and Cost Evaluation. *Materials and*
14
15 *Manufacturing Processes*, 18 (2), 313-322.
16
17
18 Chen, C. H., Occena, L.G., and Fok, S.C., 2001. CONDENSE:A Concurrent Design Evaluation System
19
20 for Product Design. *International Journal of Production Research*, 39 (3), 413-433.
21
22
23 Chen, Y. M., Miller, R.A., Sevenler, K., 1995. Knowledge-based Manufacturability Assessment: An
24
25 Object-oriented Approach. *Journal of Intelligent Manufacturing*, 6 (5), 321-337.
26
27
28 Chen, Y. M., Wen, C.C. and Ho, C.T. , 2003. Extraction of Geometric Characteristics for
29
30 Manufacturability Analysis. *Robotics and Computer Integrated Manufacturing*, 19 (4), 371-385.
31
32
33 Cherian, R. P., Midha, P.S., Smith, L.N., and Pipe, A.G., 2001. Knowledge based and Adaptive
34
35 Computational Techniques for Concurrent Design for Powder Metallurgy Parts. *Advances in*
36
37 *Engineering Software*, 32 (6), 455-465.
38
39
40 Dissinger, T. E., Magrab, E.B., 1996. Geometric Reasoning for Manufacturability Evaluation-Application
41
42 to Powder Metallurgy. *Computer-Aided Design*, 26 (10), 783-794.
43
44
45 Gebresenbet, T., Jain, P.K., and Jain, S.C., 2002. Preliminary Manufacturability Analysis Using feature-
46
47 function - Resource Considerations for Cylindrical Machined Parts. *International Journal of*
48
49 *Computer Integrated Manufacturing*, 15 (4), 361-378.
50
51
52 Giachetti, R. E., 2005. Integrating Hypermedia Design Concepts with A Systems Analysis and Design
53
54 Methodology to Develop Manufacturing Web Applications. *International Journal of Computer*
55
56 *Integrated Manufacturing*, 18 (4), 329-340.
57
58
59 Giachetti, R. E., Alvi, M.I., 2001. An Object-oriented Information Model for Manufacturability Analysis
60
of Printed Circuit Board Fabrication. *Computers in Industry*, 45 (2), 177-196.

- 1
2
3 Giannakakis, T., Vosniakos, G.C., 2006. *Sheet Metal Cutting and Piercing Operations Planning and Tools*
4
5 *Configuration by an Expert System* [online]. International Journal of Advanced Manufacturing
6
7 Technology. Available from: <http://www.springerlink.com/content/fqg0t5650k757568/fulltext.pdf>
8
9 [Accessed 16 January, 2007].
10
11
12 Gu, Z., Zhang, Y.F., and Nee, A.Y.C, 1997. Identification of Important Features for Machining Operations
13
14 Sequence Generation. *International Journal of Production Research*, 35 (8), 2285 - 2307.
15
16
17 Gupta, S. K., Arni, R., and Chen, Y. , 2003. *Web-based Manufacturability Analysis* [online]. Available
18
19 from: <http://www.glue.umd.edu/~skgupta/> [Accessed 16 January 2007].
20
21
22 Gupta, S. K., Nau D.S., 1995. Systematic Approach to Analysing the Manufacturability of Machined
23
24 Parts. *Computer-Aided Design*, 27 (5), 322-345.
25
26
27 Gupta, S. K., Nau, D.S. and Regli, W.C. , 1998. IMACS: A Case Study in Real-World Planning, *IEEE*
28
29 *Intelligent Systems*, 13 (3), 49-60.
30
31
32 Gupta, S. K., Regli, W.C., Das, D. and Nau, S., 1997. Automated Manufacturability Analysis: A Survey.
33
34 *Research in Engineering Design*, 9 (3), 168-190.
35
36
37 Gurney, K., 1997. *An Introduction to Neural Networks*. Taylor and Francis.
38
39 Hayes, C. C., 1996. Plan-based Manufacturability Analysis and Generation of Shape-changing Redesign
40
41 Suggestions. *Journal of Intelligent Manufacturing*, 7 (2), 121-132.
42
43
44 Hopgood, A. A., 1993. *Knowledge-based System for Engineers and Scientists*. . CRC Press, Inc.
45
46 Horvath, L., Rudas, I.J., Machado, J.A.T. and Hancke, G.P. , 1999. "Application of Part Manufacturing
47
48 Process Model in Virtual Manufacturing", 1999 IEEE International Symposium on Industrial
49
50 Electronics (ISIE '99), 1367- 1372.
51
52
53 Howard, L., Lewis, H., 2006. Support Tool for Material and Process Combinations During Early Design.
54
55 *International Journal of Production Research*, 44 (17), 3379-3390.
56
57
58 Jacob, D. V., Ramana, K.V. and Rao, P.V.M., 2004. Automated Manufacturability Assessment of
59
60 Rotational Parts by Grinding. *International Journal of Production Research*, 42 (3), 505-519.

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- Jacquel, D., Salmon, J., 2000. Design for Manufacturability: A Feature-Based Agent-Driven Approach. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 214 (10), 865-879.
- Jia, H. Z., Ong, S.K., Fuh, J.Y.H., Zhang, Y.F., and Nee, A.Y.C. , 2004. An Adaptive and Upgradeable Agent-based System for Coordinated Product Development and Manufacture. *Robotics and Computer-Integrated Manufacturing* 20 (2), 79-90.
- Jiang, B. C., Hsu, C.H., 2003. Development of a Fuzzy Decision Model for Manufacturability Evaluation. *Journal of Intelligent Manufacturing*, 14 (2), 169-181.
- Korosec, M., Balic, J. and Kopac, J., 2005. Neural Network based Manufacturability Evaluation of Free Form Machining. *International Journal of Machine Tools and Manufacture*, 45 (1), 13-20.
- Krishnan, S., 1997. *Design for Manufacture: An Integrated System for Injection Moulding and Milling*. Thesis (PhD). University of Maryland College Park.
- Kumar, S., Singh, R. and Sekhon G.S., 2006. CCKBS: A Component Check Knowledge-based System for Assessing Manufacturability of Sheet Metal Parts. *Journal of Material Processing Technology*, 172 (1), 64-69.
- Lee, R. S., Chen, Y.M. and Lee, C.Z., 1997. Development of a Concurrent Mold Design System: A Knowledge-based Approach. *Computer Integrated Manufacturing Systems*, 10 (4), 287-307.
- Li, J., Gao, S., and Liu, Y., 2006. *Solid-based CAPP for surface micromachined MEMS devices* [online]. Computer-Aided Design. Available from: <http://dx.doi.org/10.1016/j.cad.2006.08.006> [Accessed 31 January 2007].
- Lu, S. C., 1996. *Volume-based Geometric Reasoning and Visualization to Support Manufacturability Evaluation in Die Casting*. Thesis (PhD). The Ohio State University.
- Marquez, M., White, A., and Gill, R., 2001. A Hybrid Neural Network-feature-based Manufacturability Analysis of Mould Reinforced Plastic Parts. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 215 (8), 1065-1079.

- 1
2
3 Medani, O., 2005. *Distributed early manufacturability assessment using STEP AP224 and XML*. Thesis
4
5 (PhD). University of Nottingham.
6
7
8 Medani, O., Ratchev, S.M. , 2006. A STEP AP224 Agent-based Early Manufacturability Assessment
9
10 Using XML. *International Journal of Advanced Manufacturing Technology* 27 (9-10), 854-864.
11
12
13 Myint, S., Tabucanon, M.T., 1998. The framework for an expert system to generate alternative products in
14
15 concurrent engineering design. *Computers in Industry*, 37 (2), 125 - 134.
16
17
18 Nasr, E. A., Kamrani, A.K., 2007. *Computer-Based Design and Manufacturing: An Information-based*
19
20 *Approach*. New York, USA: Springer Science+Business Media, LLC.
21
22
23 Ong, S. K., Chew, L.C., 2000. Evaluating the Manufacturability of Machined Parts and Their Setup Plans
24
25 *International Journal of Production Research*, 38 (11), 2397-2415.
26
27
28 Ong, S. K., Nee, A.Y.C., 1996. An Intelligent Fuzzy Set-up Planner for Manufacturability and
29
30 Fixturability Evaluations. *International Journal of Production Research*, 34 (3), 665-686.
31
32
33 Ong, S. K., Sun, M.J. and Nee, A.Y.C., 2003. A Fuzzy Set AHP-based DFM Tool for Rotational Parts.
34
35 *Journal of Material Processing Technology*, 138 (1-3), 223-230.
36
37
38 Ramana, K. V., Rao, P.V.M., 2005. Automated Manufacturability Evaluation System for Sheet Metal
39
40 Components in Mass Production. *International Journal of Production Research*, 43 (18), 3889-
41
42 3913.
43
44
45 Ramana, K. V., Singh, M., Gupta, A., Dey, R., Kapoor, A. and Rao, P.V.M., 2006. A Manufacturability
46
47 Advisor for Spun and Roll formed Sheet Metal Components. *International Journal of Advanced*
48
49 *Manufacturing Technology*, 28 (3-4), 249-254.
50
51
52 Rao, S. K., 1994. *The Development of Fuzzy Cognitive Map for Manufacturability Analysis Based on Part*
53
54 *Features*. MS thesis. Texas A&M University-Kingsville.
55
56
57 Rao, S. S., Nahm, A., Shi, Z., Deng, X. and Syamil, A., 1999. Artificial Intelligence and Expert System
58
59 Applications in New Product Development - A Survey. *Journal of Intelligent Manufacturing*, 10
60
61 (3-4), 231-244.

- 1
2
3 Ravinwongse, R., 1997. *An Intelligent Design Tool for Manufacturability Evaluation of Injection Molded*
4
5 *Parts*. Thesis (PhD). University of Missouri-Rolla.
6
7
- 8 Saaty, T. L., Vargas, L.G. , 2001. *Models, Methods, Concepts & Applications of the Analytic Hierarchy*
9
10 *Process*. Springer.
11
- 12 Sanchez, J. M., Priest, J.W. and Soto, R., 1997. Intelligent Reasoning Assistant for Incorporating
13
14 Manufacturability Issues into the Design Process. *Expert Systems with Applications*, 12 (1), 81-88.
15
- 16 Scherer, K. P., Buchberger, P., Eggert, H., Stiller, P. and Stucky, P., 1996. Knowledge based Support for
17
18 Manufacturing of Microstructures. *Microsystem Technologies*, 2 (4), 167-170.
19
- 20 Shiau, J. Y., 2001. *Web-enabled environment for manufacturability assessment*. Thesis (PhD). University
21
22 of Nottingham.
23
24
- 25 Shiau, J. Y., Ratchev, S.M., and Valtchanov, G., 2000. "Distributed Collaborative Design and
26
27 Manufacturability Assessment for Extended Enterprise in XML-based Agent System", 9th IEEE
28
29 International Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises
30
31 (WET ICE 2000) Gaithersburg,MD, 260-265.
32
33
- 34 Smith, L. N., Midha P.S., 1999. A Knowledge Based System for Optimum and Concurrent Design, and
35
36 Manufacture by Powder Metallurgy Technology. *International Journal of Production Research*, 37
37
38 (1), 125 - 137.
39
40
- 41 Tharakan, P. V., Zhao, Z., and Shah, J., 2003. "Manufacturability Evaluation Shell: A Reconfigurable
42
43 Environment for Technical and Economic Manufacturability Evaluation." Design Engineering
44
45 Technical Conferences and Computers in Information in Engineering Conference (DETC'03),
46
47 Chicago, 1-10.
48
49
- 50 Venkatachalam, A. R., Mellichamp, J.M. and Miller D.M., 1993. A Knowledge-based Approach to design
51
52 for Manufacturability. *Journal of Intelligent Manufacturing*, 4 (5), 355-366.
53
54
55
56
57
58
59
60

- 1
2
3
4 Yang, W., Ding, H. and Xiong, Y., 1999. Manufacturability Analysis for a Sculptured Surface Using
5
6 Visibility Cone Computation. *International Journal of Advanced Manufacturing Technology*, 15
7
8 (5), 317-321.
9
- 10 Yuyin, S., Bopeng, Z., Fuzhi, C. and Qingguo, M. , 1996. "A Knowledge-based Design for Manufacture
11
12 System", IEEE International Conference on Systems, Man and Cybernetics 1996, Beijing, China,
13
14 1220- 1224.
15
- 16
17 Zha, X. F., Du, H., 2003. Manufacturing Process and Material Selection in Concurrent Collaborative
18
19 Design of MEMS Devices. *Journal of Micromechanics and Microengineering*, 13 (5), 509-522.
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

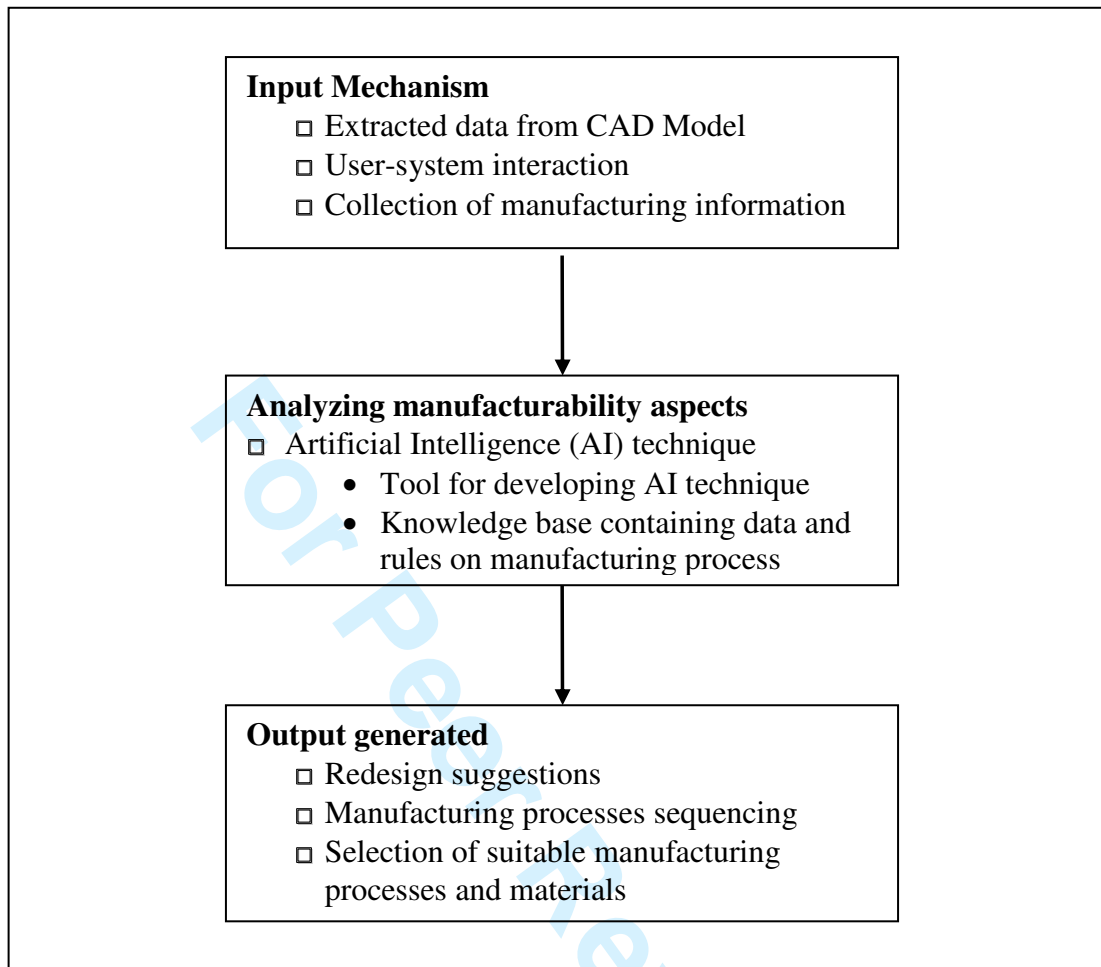


Figure 1: Basic methodology of MAS development

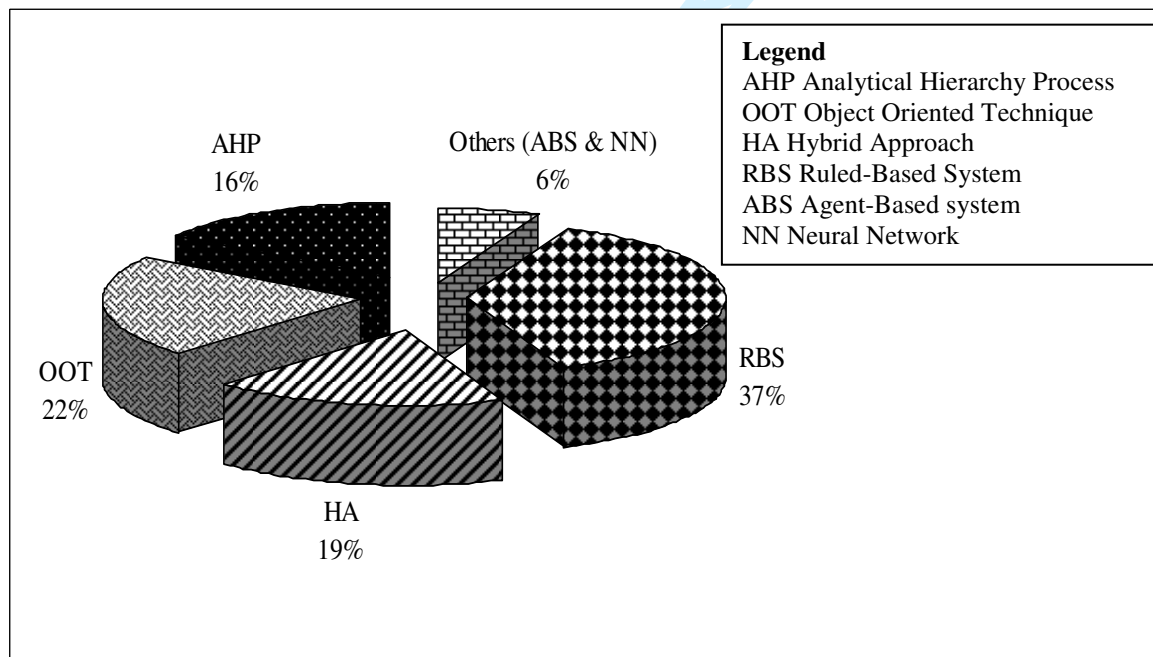


Figure 2: Type of approach used for modelling ES for MAS

Table 1: Distribution of ES tools

ES shells	Toolkits	Programming languages for AI	Conventional programming languages
<ul style="list-style-type: none"> • CLIPS (Chan 2003; Giannakakis 2006) 	<ul style="list-style-type: none"> • Nexpert (Venkatachalam 1993; Chen 1995; Amalnik 1996; Lee 1997; Amalnik 1998) • EXPRESS (Giachetti 2001; Giachetti 2005) 	<ul style="list-style-type: none"> • Auto LISP (Hayes 1996; Myint 1998; Smith 1999; Howard 2006; Kumar 2006) • Prolog (Arezo 2000) 	<ul style="list-style-type: none"> • C++ (Krishnan 1994; Scherer 1996; Sanchez 1997; Ong 2000; Jacob 2004; Korosec 2005; Ramana 2005; Ramana 2006) • Java (Zha 2003)

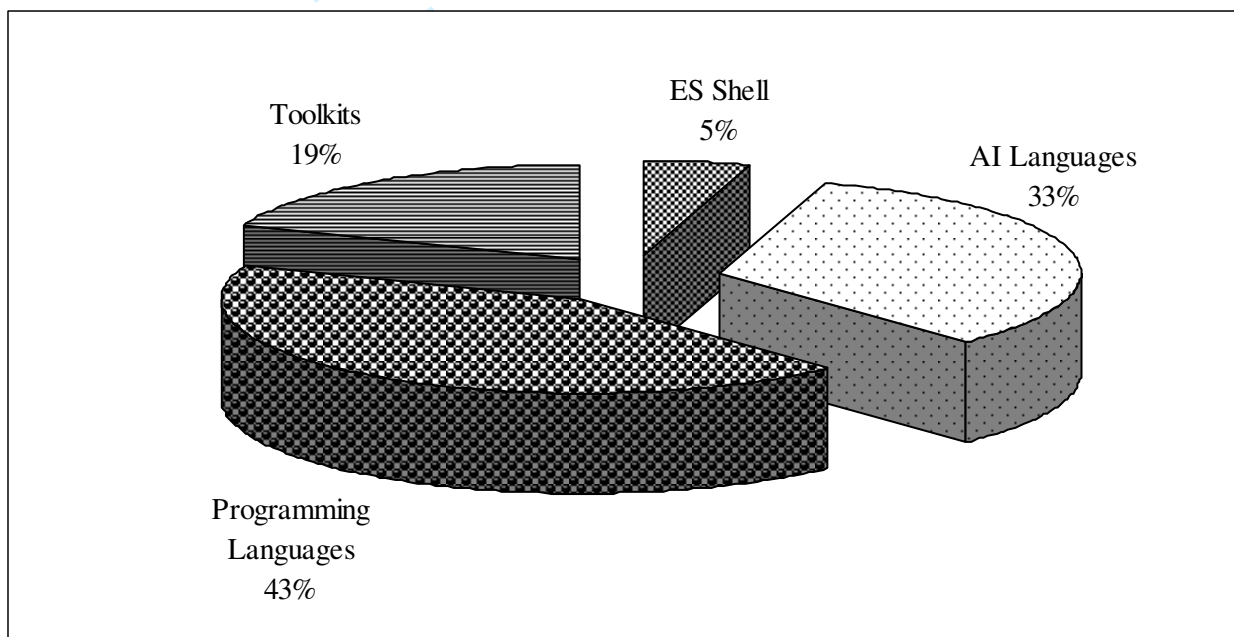


Figure 3: Distribution of tools used in developing ES

Table 2: Categories of manufacturing processes implemented with MAS

	CATEGORY			
	Casting	Forming and Shaping	Machining	Others
Process and Papers related	<ul style="list-style-type: none"> Die/Sand Casting (Venkatachalam 1993; Chen 1995; Lu 1996; Feng 1998; Tomovic 2006) 	<ul style="list-style-type: none"> Spinning (Jiang 2003; Ramana 2006) Forging (Venkatachalam 1993) Powder Metallurgy (Dissinger 1996; Smith 1999; Cherian 2001) Roll Forming (Ramana 2006) Injection Moulding (Krishnan 1997; Lee 1997; Ravinwongse 1997; Marquez 2001; Chen 2003; Tharakan 2003) Blanking/Piercing (Ramana 2005; Giannakakis 2006) Fabricating Sheet Metal (Sanchez 1997; Ramana 2005; Kumar 2006; Ramana 2006) 	<ul style="list-style-type: none"> Turning (Arezoo 2000; Jiang 2003; Ong 2003) Milling (Venkatachalam 1993; Yuyin 1996; Krishnan 1997; Jacquel 2000; Gebresenbet 2002; Tharakan 2003) Drilling (Venkatachalam 1993; Jacquel 2000; Gebresenbet 2002) Grinding (Gebresenbet 2002; Jacob 2004) Boring (Ong 2003) Wire-Electro-Discharge Machining (Amalnik 1998) Machining Processes based on shape of the fabricated part (cylindrical/prismatic part) (Yannoulakis 1991; Hayes 1996; Gu 1997; Myint 1998; Gebresenbet 2002; Ong 2003; Jacob 2004) Free-Form Machining (Yang 1999; Yang 1999; Gupta 2003; Korosec 2005) Electro-Chemical Machining (Amalnik 1996) Planing (Gebresenbet 2002) Shaping (Gebresenbet 2002) 	<ul style="list-style-type: none"> PCB fabrication (Giachetti 2001; Giachetti 2005) MEMS processes (Zha 2003; Li 2006) LIGA (Scherer 1996)

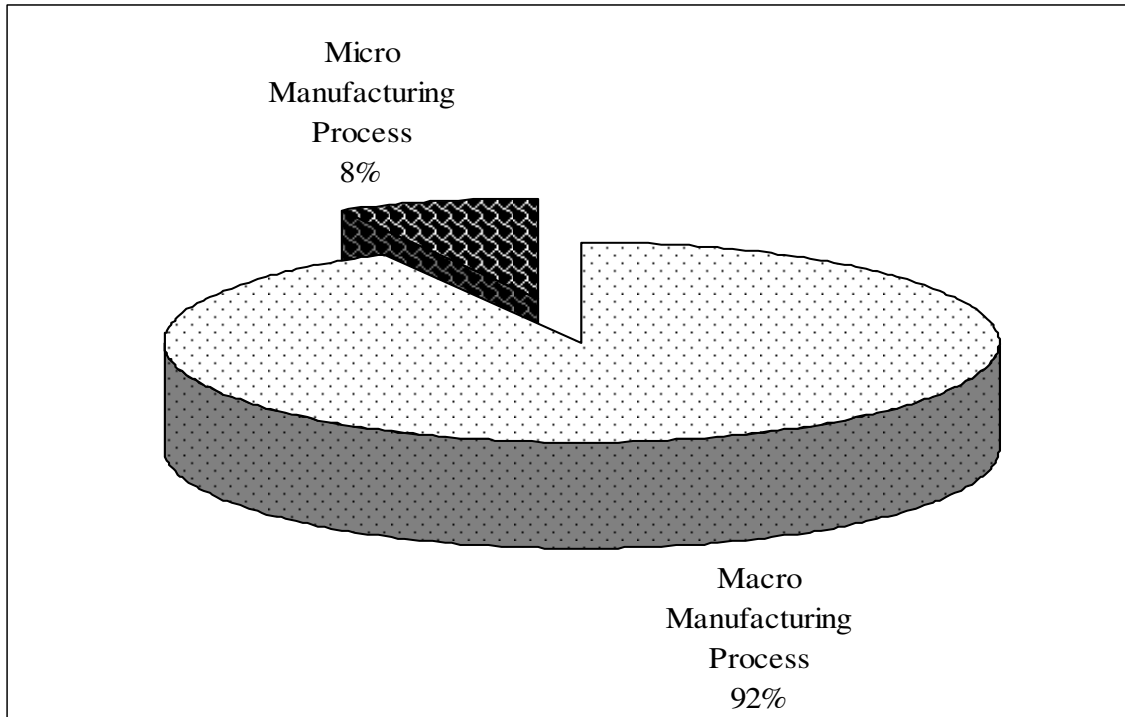


Figure 4: Distribution of MAS applicability towards two areas of manufacturing process