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Technology Maturity Assessment of Micro and Nano Manufacturing Processes and Process Chains

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Abstract

The paper presents a systematic approach for assessing the maturity of manufacturing technologies. A methodology is proposed that is based on modelling the capability of the individual processes and technology interfaces between them. It is inspired by a capability maturity model which has been applied successfully in the field of software engineering. The methodology was developed to assess the maturity levels of individual processes and the combined maturity of pairs or chains of processes. To demonstrate its validity, it was applied for assessing the maturity of technologies in the micro and nano manufacturing domain. The results from this pilot application are discussed and conclusions made about the applicability of the proposed methodology.

Keywords: Micro Manufacture, Nano Manufacture, Technological Interfaces, Process Chains, Technology Maturity, Technology Readiness, Maturity Assessment

1. Introduction

The global market for miniaturised products has been increasing continuously in the last

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decade[1]. This demand for micro-products and components has risen rapidly across many industrial sectors, especially in the electronics, optics, medical, biotechnology, automotive, communication and avionic industries [2,3]. Examples of specific applications/products are medical implants, micro-scale pumps, valves and mixing devices, micro-fluidic systems, micro-optics, micro-nozzles and micro-molds.

This trend towards product miniaturization has brought with it a number of associated product development trends. In particular, designers aim and tend to develop new products that integrate a variety of functions, thus broadening the products' application areas whilst simultaneously significantly reducing cost, size, material usage and power consumption.To satisfy specific functional and technical requirements, single components in such devices often integrate micro and nano scale structures [4]. Consequently, such a trend for "function integration" necessitates the creation of manufacturing capabilities for "length scale integration" at component and product levels. For example, the development of new devices that require the manufacture of parts incorporating three dimensional (3D) functional features covering the whole range of sizes from few 100 μm to sub-100 nm. [5]. In addition, function integration relies on and necessitates the introduction of new specially developed materials[6–9] in order to benefit from their "optimized" properties for micro and nano scale processing.

As the same time individual micro and nano manufacturing technologies that underpin the development of such products have their limitations/constraints and cost effective processing windows in regards to the length scale of features and materials that can be processed, complexity of the structures and the production rates that can be achieved [10]. Therefore, in practice, miniaturised devices with a complex geometry, which incorporate different length scale features cannot be produced by employing a single fabrication technology. An integration of several compatible and at the same time complementary micro and nano manufacturing technologies (MNT) in process chains is required to produce such devices in required quantities cost effectively. Thus, it is not surprising that the design and validation of such process chains has attracted the attention of researchers and some successful implementations have been reported to address specific functional and technical requirements of emerging multi-material products[11–16] .

However, the manufacture of micro products using such process chains is still in its infancy, and thus further research is required to characterize existing process chains, and also to develop new ones for the fabrication of miniaturized multi-material products. This prompts the research community to look for systematic approaches to assess such process chains at the technology and platform levels. At the technology level, the interfaces between component manufacturing technologies in such process chains should be analyzed in order to assess both their individual and combined capabilities, and also their compatibility and complementarity. While at the platform level, it is important to develop a tool for evaluating the “maturity” of process chains as potential manufacturing platforms for producing miniaturized products. Both types of analysis will also lead to ideas for new process chains, and will represent an objective means for assessing the risks associated with the adoption and implementation of these technologies and the manufacturing platforms underpinned by them[17]. In addition, the ability to assess the “maturity” of the technologies in process chains will also provide a means for benchmarking them [18] . Such benchmarking could be used for ranking purposes, and therefore could eventually be applied for process chain selection when there are alternative competing solutions for the fabrication of a given micro component [18]. In this context, the objective of this research is to develop and validate a systematic approach for assessing the maturity of technologies in the micro and nano manufacturing (MNM) domain.

The paper is structured as follows. After reviewing a number of maturity assessment techniques, a method for assessing the maturity of MNM processes and process chains is presented. Then, a pilot application of this methodology on a set of MNM processes is described to demonstrate its capabilities. Finally, the results from this pilot application are discussed and conclusions made about the viability of the proposed methodology.

2. A review of technology maturity assessment approaches.

A popular concept for assessing the maturity of technologies is the Technology Readiness Level (TRL). The TRL concept represents a systematic metric/measurement system that is designed to assess the maturity of a given evolving technology and also to compare the maturity of different technologies[19] . The assessment is based on a scale from 1 to 9, and generally, if a technology is more developed, the higher is its TRL. The TRL concept and the associated scale were developed over two decades, in particular from mid-1970s to the mid-1990s by the National Aeronautics and Space Administration (NASA) [20,21]. Since their inception, the TRLs have been used within organisations such as NASA, the United States Department of Defence, the Air Force Research Lab, the European Space Agency and the Turkish defence industry[20–23] for measuring the maturity of technologies utilised in military and aerospace systems. In addition, it was proposed to use the TRL concept for monitoring the maturity of emerging technologies[24] and also for evaluating the readiness of software products[23]. Recently, Brousseau et al[17] proposed a methodology inspired by the TRL concept that utilises a common scale composed of seven "maturity phases" for assessing the MNM processes' maturity. This approach was designed to overcome some of the limitations of the TRL concept. Especially, the proposed methodology was developed to simplify the maturity evaluation procedure by combining a large number of inputs from rich and validated knowledge repositories, e.g. in the form of portfolios of R&D projects. Furthermore, Reinhart and Schindler[25] proposed an approach for evaluating the maturity of a manufacturing technology by combining the technology maturity assessment approach proposed by Brousseau et al[17] with the technology life cycle concept of Ford & Ryan[26]. However, these two approaches do not provide a means for assessing the maturity of process chains that integrate more than one constituent manufacturing technology.

Other maturity assessment approaches find their origins in the field of quality management. One of the earliest of these is Crosby's quality management maturity grid[27] , which was designed to evaluate the status and evolution of an organisation's approach to quality management at five levels of maturity. One of the best-known derivatives from this approach is the capability maturity model (CMM) in software engineering. The software CMM was introduced by Humphrey[28] and subsequently elaborated further by the Software Engineering Institute (SEI) at Carnegie Mellon University[29] . It is a comprehensive model for a continuous software development that describes an evolutionary improvement path for software organizations from an adhoc, chaotic, and immature process to a mature and disciplined one. In particular, it classifies processes and organizations into five levels of maturity based on the underlying engineering and management practices that characterize them, namely: (i) Initial, (ii) Repeatable, (iii) Defined, (iv) Managed and (v) Optimized. This SEI CMM has been applied by thousands of organizations[30] and also has inspired the development of other models that address the specific capabilities required for specialised applications. These multiple models have been consolidated into the Capability Maturity Model Integration (CMMI) approach which is a process improvement maturity model for the development of products and services[31]. The concepts of process or capability maturity are increasingly being applied to a range of activities, both as a means of assessment and also as part of a framework for improvements. In particular, CMM/CMMI based maturity models were proposed for a diverse range of activities such as assessment of electronic products' reliability, knowledge management, product development collaborations, risk management in complex product development projects and manufacturing engineering, and project management[32–37]. However, the existing body of literature reveals that, to date there are no CMM-based maturity models for assessing manufacturing processes and process chains despite the potential benefits that this approach can offer in this domain.

In this context, the focus of this research is to propose and validate a methodology for systematic assessment of the maturity of individual MNM processes and process chains inspired by the CMM approach[29]. The proposed methodology can be utilised as a platform for assessing systematically the maturity of both individual micro and nano manufacturing technologies and also their combinations into process chains. The proposed methodology can be used also as a tool for identifying factors affecting the uncertainty associated with the implementation of MNM processes and process chains in manufacturing platforms and also for defining strategies to manage it.

3. Methodology

The proposed methodology represents a combination of top down and bottom up approaches for assessing maturity of technologies/processes as depicted in Fig. 1. It is a tool to model the maturity of component technologies and their possible integrations in process pairs and chains. The methodology provides a means to assess such process chains at the technology and platform levels.

At the technology level, the component technologies in process chains are modeled as process pairs as shown in Fig.2. The ‘process chains’, ‘individual processes’, ‘process pairs’ and ‘technological interface’ between individual processes are the four major paradigms of the proposed approach. Each individual process in a pair or a chain executes a specific manufacturing operation and represents a basic “component” technology (e.g. “micro milling”) in satisfying the technical requirements of a product. Thus, process chains include a number of process pairs and each pair combines the capabilities of two component technologies, with a specific interface between them. In each process pair, the output of the first process becomes the input of the second one, which creates complex interdependencies that define the so-called technological interface between the component technologies[38,39] . By implementing the concept of technological interfaces between two consectutive processes, a link between the processes is established and the effect of their combined set of capability parameters on the performance of a process pair can be modelled and assessed. Thus, at the technology level, the interfaces between component manufacturing technologies in such process chains are systematically analyzed in order to assess both their individual and combined capabilities, and also their compatibility and complementarity. At the same time at the platform level, this modelling approach allows the "maturity" of process chains to be assessed as potential manufacturing platforms for producing miniaturized products. Finally, the methodology allows informed inputs from MNM process experts to be utilised in assessing the maturity of processes and pairs. A detailed description of the proposed methodology is given in the subsequent sections.

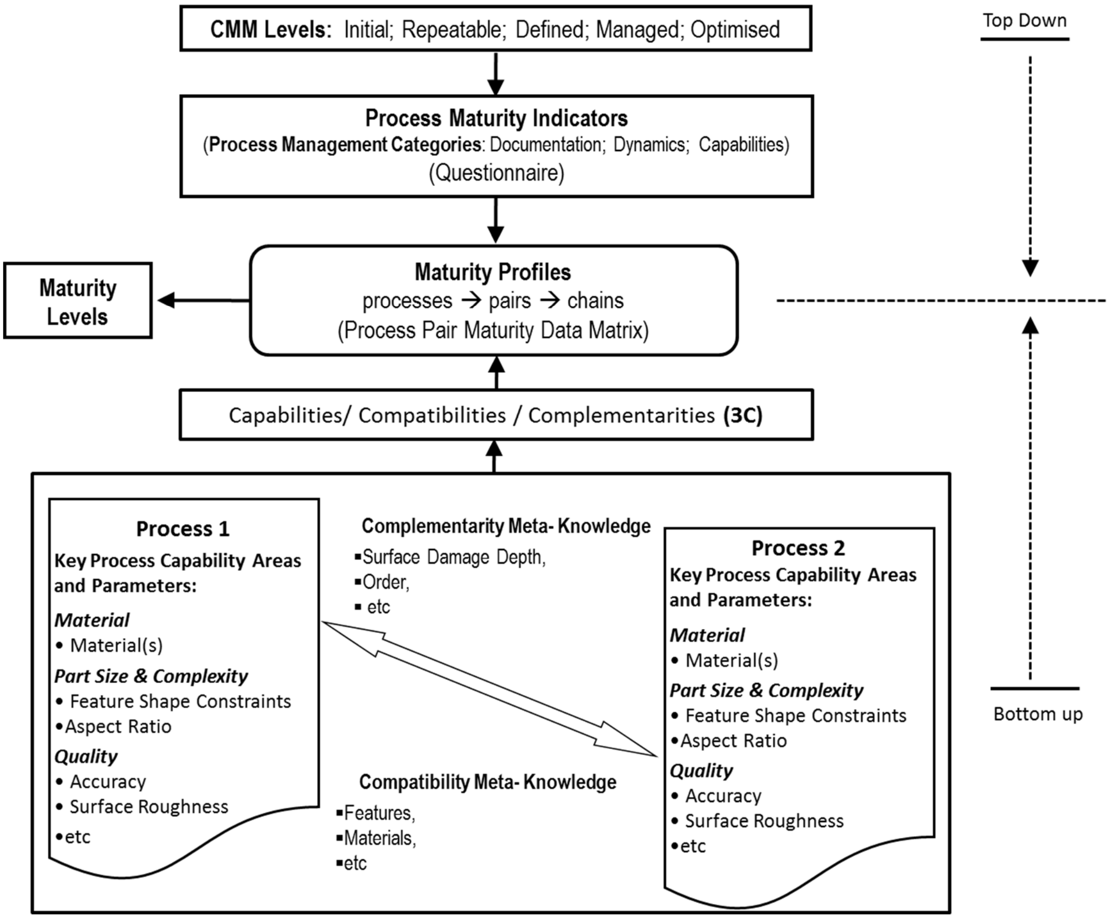


Fig 1. Schematic representation of the overall methodology

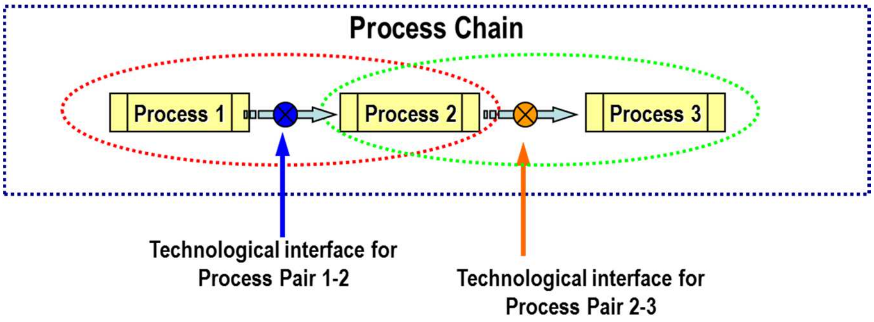


Fig 2. Process pairs and process pair technological interfaces

3.1 The top down approach

The top down approach for assessing manufacturing processes is based on the CMM in software engineering. Maturity is defined as “a state of being fully grown or developed”[40] . From a manufacturing view point, maturity implies that a process is well understood, documented, and formal training is available while it is consistently applied in practice and is continuously monitored and improved. So, it is possible to state that the performance and the overall behaviour of such a process are highly predictable. Therefore, the maturity assessment of a process or process pair provides a means to estimate the likelihood of achieving particular process outcomes when it is used to fabricate a given part or feature.

This definition of maturity conveys the notion of development from some initial state to some more advanced states as a result of continuous process improvements. Also, implicit in this, is the notion of evolution, suggesting that a manufacturing process or process pair may pass through a number of intermediate states on the way to maturity. Thus, maturity levels are well-defined evolutionary stages towards achieving a mature manufacturing process or process pair. Therefore, the CMM’s five level maturity structure was adopted in the proposed methodology. Each maturity level can be scrutinized from abstract summaries down to a more detailed operational description in the form of Process Maturity Indicators (PMI) (See Fig 1). These are specific indicators which describe typical benchmarking activities, characteristics and performance metrics that a process should achieve or exceed for each maturity level. In addition, PMI can be associated with process management categories, in particular, documentation, dynamics and capabilities, as they are defined in Table 1. An example of a PMI in the context of manufacturing processes is the existence of a good agreement between modelling/simulation results and the actual process performance in a given environment.

Table 1: Process management categories

Category	Description
Documentation	This represents the status of the documentation related to a specific manufacturing process. This category describes the type of documentation related activities/ characteristics needed to ensure that the process is established and will endure. Typical documentation items include but are not necessarily limited to scientific papers and internal reports, training material, trade magazine articles, books, guidelines available from equipment manufacturers, standards, procedures, etc.
Dynamics	This defines the level of change related to the capability of a specific manufacturing process. It describes the type of activities and characteristics that lead to changes and improvements in the process performance. For example, are the processing windows for various materials still under development or have they been defined? Obviously in this case, the higher the number of materials with defined processing windows, the higher is the process maturity level.
Capabilities	This defines the level of consistency in achieving the expected outcomes by implementing a specific manufacturing process. It describes the type of activities and characteristics that indicate whether a manufacturing process is consistently achieving the targeted performance and capabilities.

To apply the proposed top down approach it is necessary to identify sets of specific PMI associated with the three process management categories in Table 1. In particular, such sets of PMI can be identified through brainstorming or Delphi-type workshops with experts in a given manufacturing domain. Then, these sets of PMI are used to create maturity assessment questionnaires with documentation, dynamics and capabilities subsections that can be used to obtain expert judgments about the most representative characteristics of processes in any considered manufacturing domain. In particular, the goal of each question in such a survey is to verify whether a specific PMI has been achieved or otherwise and therefore can be used to describe the current process state. Thus, in practice, the maturity level reached by a given process in the top down approach is determined by PMI characterizing its current state in regards to its overall behaviour, performance and operational environment.

3.2. The bottom up approach

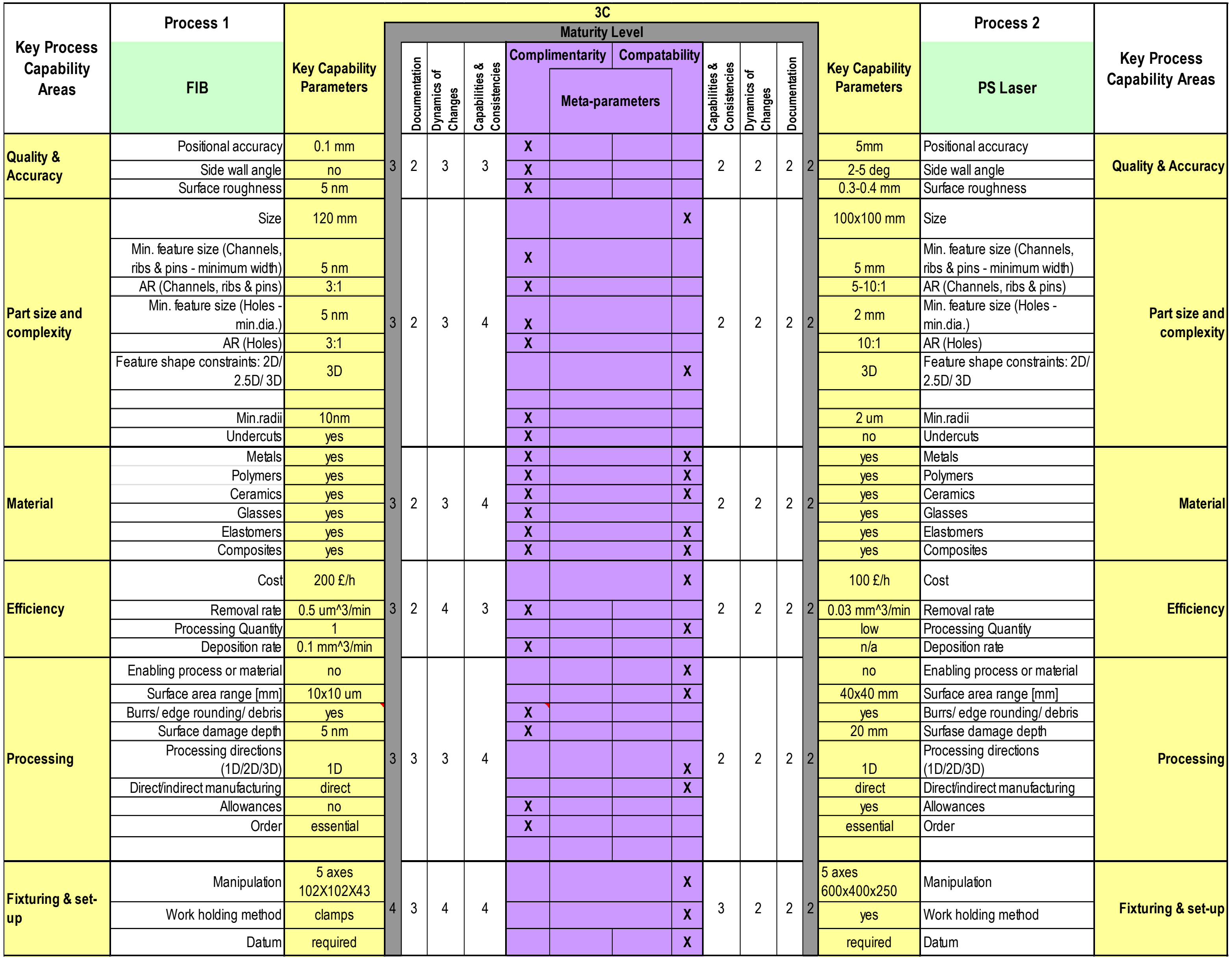
In the proposed methodology, the top down approach is complemented by a bottom up approach for assessing component technologies in process chains. More specifically, it is necessary to analyze the compatibility and complementarity of component technologies in such process chains[6]. In this context, the proposed approach to model the technological interface of a given process pair takes into account the capabilities of its two component technologies, their dependencies and also the overall capabilities of the pair in producing a part with its technical requirements.

To implement the bottom up approach, a new modelling structure (see Fig 1) is necessary to represent with sufficient depth the technological interfaces between any two processes. In particular, the structure should store a set of Key Process Capability Parameters (KPCPs) that characterize the component technologies in any process pair. For example in this research 32 KPCPs have been identified as the most important factors in determining the manufacturing capabilities of the MNM processes, e.g. positional accuracy, aspect ratio, minimum feature size, side wall angle, material, removal/deposition rate, manipulation technique, work holding method, etc. An example of a structure/table to capture these 32 KPCPs is shown in Fig 3 where the parameters are grouped under 6 Key Process Capability Areas (KPCAs), namely: Quality & Accuracy; Part Size and Complexity; Material; Efficiency; Processing; and Fixturing & Set-up.

When process pairs are analyzed, in addition to the KPCPs of their component technologies, it is necessary to take into consideration their overall technological capabilities. In the proposed methodology the process pairs' capabilities are referred to as "meta-parameters" due to the combined effects of their two constituent processes in achieving the technical requirements of a given part or product[41] . In particular, the meta-parameters are additional attributes associated with the process pairs that facilitate the mapping and integration of KPCPs related to the two component technologies in each pair. The values of the meta-parameters are determined by the KPCPs of process pairs, and reflect the level of their compatibility and complementarity. KPCPs and prior experience with the constituent processes in any given pair are used to make a qualitative (expert) judgment about their compatibility and complementarity. In particular, two processes are considered only compatible if they can be combined successfully in a process pair but there is a higher level of overlapping between their capabilities. Thus, the technical requirements of a part or product can be achieved by either of them. For example, if both component technologies in a pair can process the same types of materials and can generate feature sizes within the same length scales, their associated KPCPs are mapped as compatible. Conversely, KPCPs of two processes are mapped as complementary if by using them in a sequence brings added-value or other potential benefits and thus the overall capabilities of a given process pair are enhanced. For example, the capabilities associated with the achievable "minimum feature sizes" by Pico Second (PS) laser ablation and Focused Ion Beam (FIB) machining are complementary because these two processes can be used for structuring different scale features and thus their associated KPCPs can be mapped as complementary. In particular, the minimum feature sizes achievable with FIB machining are an order of magnitude smaller than those in pico second laser ablation. Thus, it is possible to produce nano scale structures with FIB after the machining of micro scale features with the PS laser, and as a result be able to achieve the so-called length scale integration by pairing these two direct-write technologies.

In applying the bottom up approach the compatibility/complementarity meta-parameters of process pairs are created by applying a set of rules. For example, the rule for “minimum feature size” that is one of the “part size and complexity” KPCPs sub-set is as follows: if the “minimum feature size” achievable with constituent processes 1 & 2 in a process pair (pp) are not of the same order of magnitude, e.g. process 1 has much higher resolution than the follow up process, then this KPCP should be mapped as complementary. So by using this rule to analyze the FIB + PS-Laser process pair, their “minimum feature size (channels, ribs & pins)” KPCPs will be mapped as complementary as their achievable minimum feature sizes are 5nm and 5μm, respectively. The results of this “meta” analysis of KPCPs associated with process pairs are stored in Process Pair Maturity Matrixes (PPMMs), an example is given in Fig 3, that can be used to assess the capability, compatibility and complementarity (3C) of component technologies in process pairs (see Fig. 1). Then, these PPMM spreadsheets are required to estimate the maturity levels of process pairs and their constituent process.

The next section presents the five maturity levels considered in the proposed methodology and also how the top down and bottom up approaches described in this section are integrated in a model to assess maturity levels of process pairs and their constituent processes.



Key Process Capability Areas	Process 1	Key Capability Parameters	3C Maturity Level	Documentation	Dynamics of Changes	Capabilities & Consistencies	Complimentarity	Meta-parameters	Compatability	Capabilities & Consistencies	Dynamics of Changes	Documentation		Key Capability Parameters	Process 2	Key Process Capability Areas
	FIB														PS Laser	
Quality & Accuracy	Positional accuracy	0.1 mm	3	2	3	3	X			2	2	2	2	5mm	Positional accuracy	**Quality & Accuracy**
	Side wall angle	no					X							2-5 deg	Side wall angle	
	Surface roughness	5 nm					X							0.3-0.4 mm	Surface roughness	
Part size and complexity	Size	120 mm	3	2	3	4			X	2	2	2	2	100x100 mm	Size	**Part size and complexity**
	Min. feature size (Channels, ribs & pins - minimum width)	5 nm					X							5 mm	Min. feature size (Channels, ribs & pins - minimum width)	
	AR (Channels, ribs & pins)	3:1					X							5-10:1	AR (Channels, ribs & pins)	
	Min. feature size (Holes - min.dia.)	5 nm					X							2 mm	Min. feature size (Holes - min.dia.)	
	AR (Holes)	3:1					X							10:1	AR (Holes)	
	Feature shape constraints: 2D/ 2.5D/ 3D	3D							X					3D	Feature shape constraints: 2D/ 2.5D/ 3D	
	Min.radii	10nm					X							2 um	Min.radii	
	Undercuts	yes					X							no	Undercuts	
Material	Metals	yes	3	2	3	4	X		X	2	2	2	2	yes	Metals	**Material**
	Polymers	yes					X		X					yes	Polymers	
	Ceramics	yes					X		X					yes	Ceramics	
	Glasses	yes					X							yes	Glasses	
	Elastomers	yes					X		X					yes	Elastomers	
	Composites	yes					X		X					yes	Composites	
Efficiency	Cost	200 £/h	3	2	4	3			X	2	2	2	2	100 £/h	Cost	**Efficiency**
	Removal rate	0.5 um^3/min					X							0.03 mm^3/min	Removal rate	
	Processing Quantity	1							X					low	Processing Quantity	
	Deposition rate	0.1 mm^3/min					X							n/a	Deposition rate	
Processing	Enabling process or material	no	3	3	3	4			X	2	2	2	2	no	Enabling process or material	**Processing**
	Surface area range [mm]	10x10 um							X					40x40 mm	Surface area range [mm]	
	Burrs/ edge rounding/ debris	yes					X							yes	Burrs/ edge rounding/ debris	
	Surface damage depth	5 nm					X							20 mm	Surfase damage depth	
	Processing directions (1D/2D/3D)	1D							X					1D	Processing directions (1D/2D/3D)	
	Direct/indirect manufacturing	direct							X					direct	Direct/indirect manufacturing	
	Allowances	no					X							yes	Allowances	
	Order	essential					X							essential	Order	
Fixturing & set-up	Manipulation	5 axes 102X102X43	4	3	4	4			X	3	2	2	2	5 axes 600x400x250	Manipulation	**Fixturing & set-up**
	Work holding method	clamps							X					yes	Work holding method	
	Datum	required							X					required	Datum	

Fig 3. Process Pair Maturity Matrix

3.3 Model design

3.3.1 Maturity Levels.

As stated earlier, maturity levels (MLs) are well-defined evolutionary stages towards achieving mature manufacturing processes or process pairs. The five maturity levels considered in the proposed methodology are provided in Table 2. Each level represents a stage in the development and the implementation of any given process pair or its constituent processes.

Table 2. Process capability maturity levels

Levels		**Description**
Initial	**1**	***Introduction of a new process***. Undocumented and dynamically changing. Initial (chaotic, ad hoc) utilization of a new process.
Repeatable	**2**	***A process with a predictable behaviour***. Consistent and repeatable results are achievable if rigorous discipline is applied. The process is used repeatedly with predictable results.
Defined	**3**	***Standard Process.*** Subject to improvements. Defined (institutionalized) process. A process approved for given applications or product requirements.
Managed	**4**	***Validated process with a broad usage***. Adaptable to given needs/requirements. Validated process capabilities. Quantified process management and established measurement practices.
Optimized	**5**	***Process with high predictability and performance.*** Incremental innovative changes. Defined improvement objectives. Optimized management practices. Planned and well managed process optimization/ improvements.

3.3.2 Integration of top down and bottom up approaches

As can be seen in Fig 1, the top down and bottom up approaches are applied simultaneously to carry out expert- and KPCP-based assessments of the maturity levels of processes and process pairs. Fig 4 illustrates the four steps required to perform these maturity level assessments.

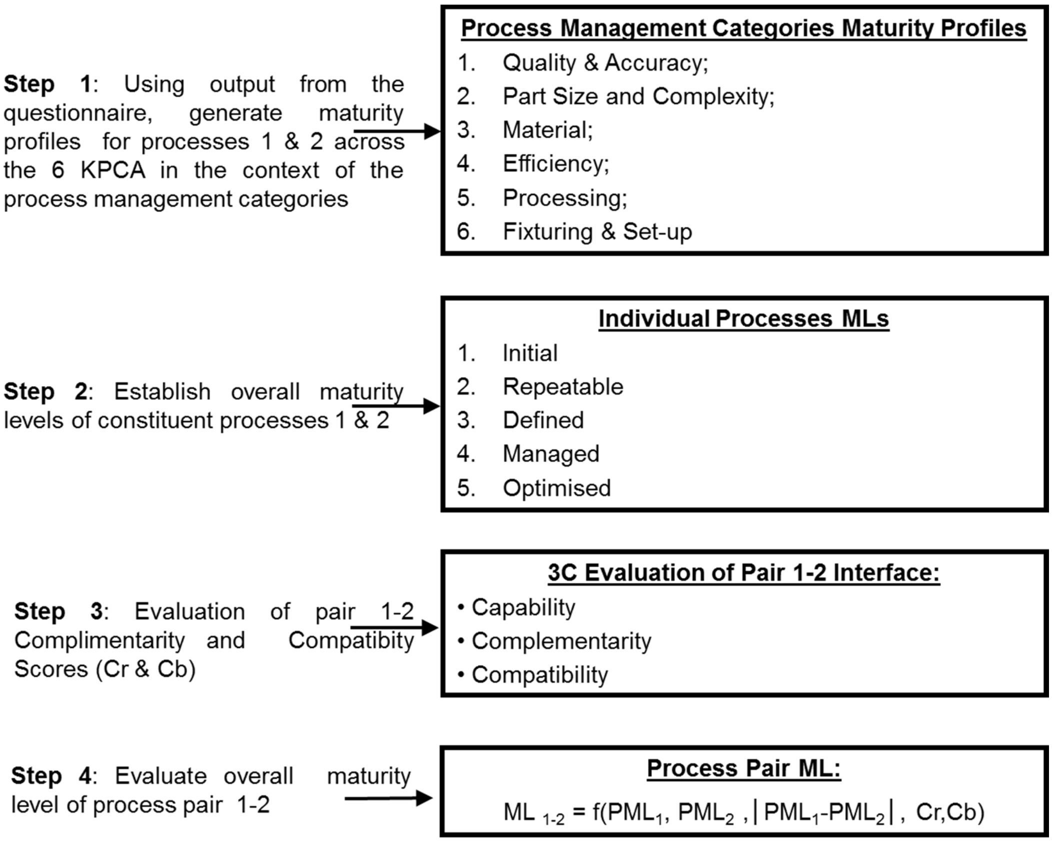
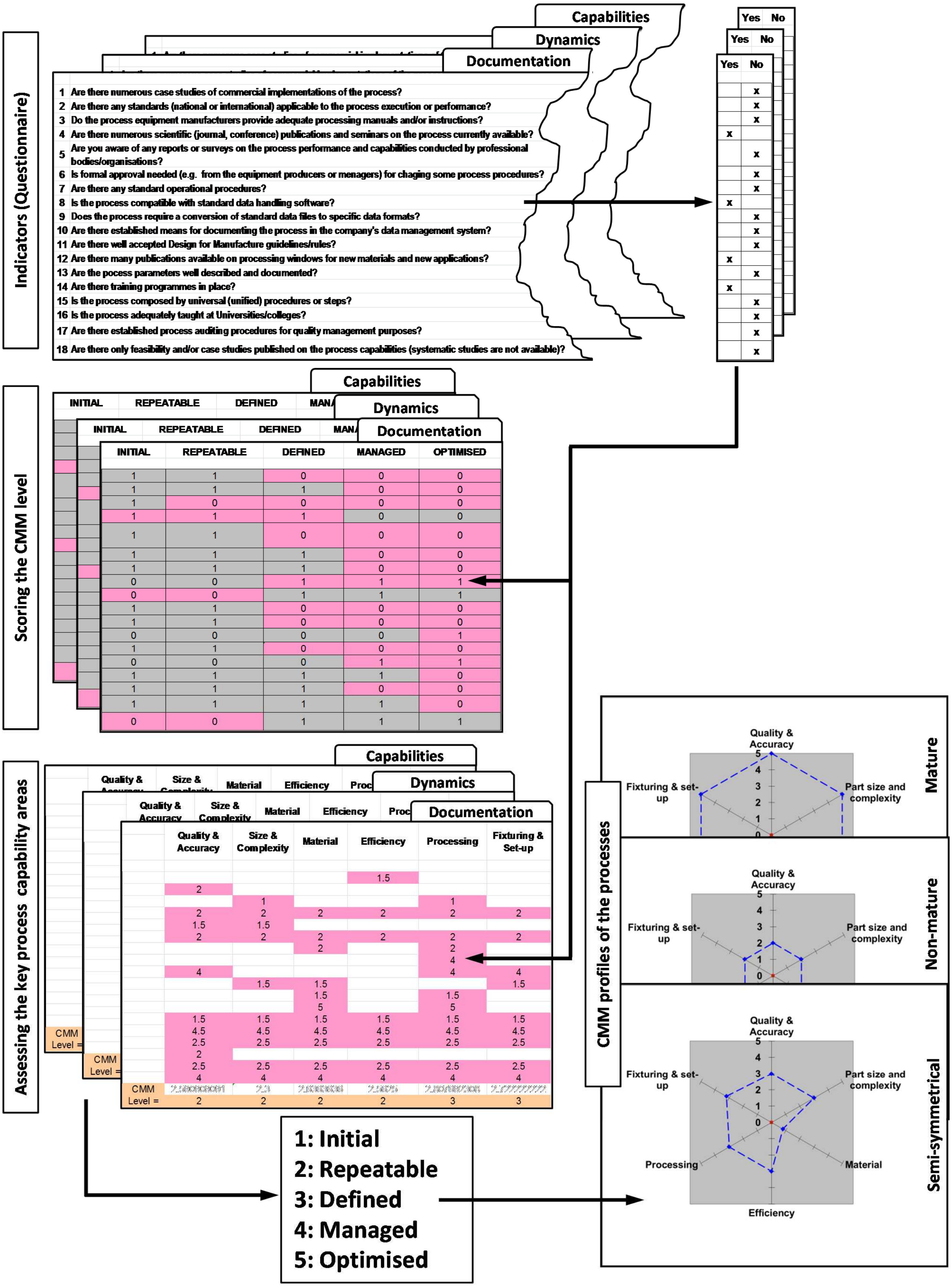


Fig 4. Individual process and process pair maturity level assessment

The maturity assessment of constituent processes in pairs is carried out in Steps 1 and 2. As discussed earlier, in practice, the maturity level reached by a given process is determined based on experts' judgments through structured questionnaires employing key indicators for each level in the process evolution. The outputs of the questionnaires allow the processes to be positioned objectively on the maturity scale irrespective of their applications. Each 'yes' or ‘no’ answer given to the maturity assessment questions relates to a specific maturity indicator and thus to determine MLs of the associated KPCAs and process management categories. For example, an indicator within the “Capabilities” process management category for the maturity of the “Part Size & Complexity”, “Material” and “Processing” KPCA could be the existence of a correlation between modeling/simulation results and actual process performance in a given environment. This approach allows not only the overall maturity of a process to be assessed but also that of its KPCAs and Process Management Categories. The practical implementation of this maturity assessment methodology for a single MNM process is illustrated in Fig.5



	Indicators (Questionnaire)	Yes	No
1	Are there numerous case studies of commercial implementations of the process?		x
2	Are there any standards (national or international) applicable to the process execution or performance?		x
3	Do the process equipment manufacturers provide adequate processing manuals and/or instructions?		x
4	Are there numerous scientific (journal, conference) publications and seminars on the process currently available?	x	
5	Are you aware of any reports or surveys on the process performance and capabilities conducted by professional bodies/organisations?		x
6	Is formal approval needed (e.g. from the equipment producers or menagers) for chaging some process procedures?		x
7	Are there any standard operational procedures?		x
8	Is the process compatible with standard data handling software?	x	
9	Does the process require a conversion of standard data files to specific data formats?		x
10	Are there established means for documenting the process in the company's data management system?		x
11	Are there well accepted Design for Manufacture guidelines/rules?		x
12	Are there many publications available on processing windows for new materials and new applications?	x	
13	Are the pocess parameters well described and documented?		x
14	Are there training programmes in place?	x	
15	Is the process composed by universal (unified) procedures or steps?		x
16	Is the process adequately taught at Universities/colleges?		x
17	Are there established process auditing procedures for quality management purposes?		x
18	Are there only feasibility and/or case studies published on the process capabilities (systematic studies are not available)?		x

INITIAL	REPEATABLE	DEFINED	MANAGED	OPTIMISED
1	1	0	0	0
1	1	1	0	0
1	0	0	0	0
1	1	1	0	0
1	1	0	0	0
1	1	1	0	0
1	1	1	0	0
0	0	1	1	1
0	0	1	1	1
1	1	0	0	0
1	1	0	0	0
0	0	0	0	1
1	1	0	0	0
0	0	0	1	1
1	1	1	1	0
1	1	1	0	0
1	1	1	1	0
0	0	1	1	1

	Quality & Accuracy	Size & Complexity	Material	Efficiency	Processing	Fixturing & Set-up
				1.5		
	2					
		1			1	
	2	2	2	2	2	2
	1.5	1.5				
	2	2	2	2	2	2
			2		2	
					4	
	4				4	4
		1.5	1.5			1.5
			1.5		1.5	
			5		5	
	1.5	1.5	1.5	1.5	1.5	1.5
	4.5	4.5	4.5	4.5	4.5	4.5
	2.5	2.5	2.5	2.5	2.5	2.5
	2					
	2.5	2.5	2.5	2.5	2.5	2.5
	4	4	4	4	4	4
CMM	2.590909091	2.3	2.636363636	2.5625	2.807692308	2.722222222
Level =	2	2	2	2	3	3

1: Initial
2: Repeatable
3: Defined
4: Managed
5: Optimised

Fig 5. The methodology for the Maturity Level evaluation of a single MNM Process

Next, steps 3 and 4 in Fig 4 involve the maturity assessment of process pairs. The ML of a process pair is dependent on ML of its constituent processes, and also it depends on their compatibility and complementarity. Thus, the assessment should reflect the maturity of both technologies in a pair, and accounts for the pair's meta-parameters. The objective is to define a measure to estimate the likelihood of achieving a particular outcome when the pair is used to fabricate a part or a set of features. Such a measure should take into account various factors affecting the Process Pair Maturity Level (PP_ML), in particular: the maturity level of the 1st constituent process (PML_1), the maturity level of the 2nd process (PML_2) and also their complementarity (C_r) and compatibility (C_b).

C_b is used as an overall metric to assess the input-output compatibility of two processes when they can be combined in a pair and estimates any 'value-added' functional or economic advantages. Thus, if two processes are entirely compatible, they would be just alternative or competing technologies and hence they can have even negative effects on a process chain because without gains leads to increased complexity, higher cost and a likelihood for reliability issues. C_b can be estimated using the following formula:

$$C_b = \sum X_b \qquad (1)$$

where $\Sigma(X_b)$ is the sum of the KPCPs mapped as compatible (meta-parameters) within the overall KPCP set consisting of N capability parameters.

At the same time, C_r of a process pair is a metric for assessing whether by combining two processes, 'value-added' (or synergetic) functional or economic benefits can be gained. Thus, it is an overall measure of the perceived complementarity of two processes in enhancing each other's capabilities. A simple formula for estimating C_r should take into account the whole set of KPCPs (X_r) mapped as complementary (meta-parameters), in particular:

$$C_r = \sum X_r \tag{2}$$

The methodology was implemented into an excel-based PPMM model. By applying it not only the PP_MLs can be obtained but also the maturity profile across the 6 KPCAs in the context of the Documentation, Dynamics, and Capabilities can be analysed. The pilot application of this model on a set of MNM processes is presented and discussed in the following sections.

4. Pilot Implementation

As highlighted earlier, to implement the proposed methodology first it is necessary to identify generic indicators that can be used to characterize the current state of a given manufacturing process, preferably in the context of the targeted MNM domain. In the proposed modeling approach, expert judgments obtained through a Delphi-type workshop are used to identify them. Then, these indicators are utilized to develop a questionnaire for characterizing and positioning the MNM processes along the adopted maturity scale. The proposed modeling approach was applied to assess the maturity of 10 different state-of-the-art MNM processes integrated within an European Infrastructure program, EUMINAfab[42] . The processes considered in this study could be clustered into 4 groups, namely micro and nano patterning, thin film deposition, replication and characterization technologies.

4.1 Identification of Process Maturity Indicators and Questionnaire Design

To identify the process maturity indicators, a workshop was organized that brought together more than 40 MNM experts in all four process groups. There were three main steps in defining the questionnaire.

(i) *Identification & Classification of Process Maturity Indicators.* The maturity assessment methodology was presented at the workshop and its objectives was discussed and agreed with the experts. Then, the experts were split in two parallel groups with one moderator each to discuss and then come up with generic indicators in the context of their specific technology areas. The discussion that proceeded was very important in order for the experts to understand what kind of process characteristics could be used as indicators in the context of the whole set of considered MNM technologies and their various possible maturity levels. Then, the participants were asked to provide a set of such generic indicators that were both informative about the current state of a given process and also meaningful across the various considered MNM processes. For example, one of the key indicators identified by the experts to characterize a given process as 'Managed' (ML 4) was "process yield > 80%".

(ii) *Semantic clustering of the process maturity indicators.* To be able first to group the indicators and subsequently the structured questionnaire, the experts were asked in a follow-up session to discuss the previously identified indicators and then to group them under the adopted three Common Process Management Categories, 'Documentation', 'Dynamics' and 'Capabilities', while considering their relevance to each of the five MLs along the proposed maturity scale . In particular, for the example given above, the key indicator "process yield > 80%" was classified under the 'Capabilities' category whilst being indicative of ML 4.

(iii) *Development of a Maturity Assessment Questionnaire*. Finally, the identified indicators were used to design the questionnaire and the questions were grouped under the 'Documentation', 'Dynamics' and 'Capabilities' categories as shown in Fig 6. In addition, as the indicators were also classified along the considered 5 MLs, each question can be used to position the MNM processes, along the adopted maturity scale. When completing the developed questionnaire, the experts have to give a binary answer to each question, and thus the necessary information can be derived for assessing MLs of a given MNM process. Then, the PML for a given MNM process can be obtained by averaging the individual MLs associated with each KPCA under the three semantic categories (Documentation, Dynamics, and Capabilities). Face-to-face type interviews were the preferred mode to complete the questionnaire for the following reasons:

- Some of the questions included complex concepts, which could be difficult to interpret consistently through a self-administered questionnaire[43] ;
- The facilitators were able to assess how respondents reacted to the questionnaire and if necessary, they could clarify or explain the meaning of particular questions in order to obtain more accurate and representative responses.

Documentation

1. Are there numerous case studies of commercial implementations of the process?
2. Are there any standards (national /international) applicable to the process execution or performance?
3. Do the process equipment manufacturers provide adequate processing manuals and/or instructions?
4. Are there numerous scientific publications and seminars on the process currently available?
5. Are you aware of any reports or surveys on the process performance and capabilities conducted by professional bodies/organizations?
6. Is formal approval needed (e.g. from the equipment producers or managers) for changing some process procedures?
7. Are there any standard operational procedures?
8. Is the process compatible with standard data handling software?
9. Does the process require a conversion of standard data files to specific data formats?
10. Are there established means for documenting the process in the company's data management system?
11. Are there well accepted Design for Manufacture guidelines/rules?
12. Are there many publications available on processing windows for new materials and new applications?
13. Are the process parameters well described and documented?
14. Are there training programmes in place?
15. Is the process composed by universal (unified) procedures or steps?
16. Is the process adequately taught at Universities /colleges?
17. Are there established process auditing procedures for quality management purposes?
18. Are there only feasibility and/or case studies published on the process capabilities (systematic studies are not available)?

Dynamics

19. Is the process a dynamically changing or an ad-hoc one?
20. Is the process utilized predominantly in laboratory environment (e.g. proof of concept)?
21. Are the effects of individual process parameters on its performance still under investigation?
22. Do you consider the process outcomes repeatable in terms of accuracy, throughput yield, surface integrity, etc.?
23. Are the process' characteristics, including the measurable ones, defined and evaluated?
24. Are gauge studies performed to understand and minimize the source of measurement errors or process uncertainty?
25. Is the process easily adaptable to particular needs or requirements?
26. Do some application specific implementations of the process exist?
27. Is the process already well automated?
28. Are the objectives for process improvement / optimization well defined?
29. Are there continuous process performance improvements through both incremental and innovative technological changes achievable by applying scientific approaches?
30. Are the processing windows for various materials still under development?
31. Is the process performance/ capabilities dependant on the operator's skills/knowledge?
32. Is the process universal (unified) and are there more than one/two suppliers/producers of the equipment for the process?
33. Is the technology commercialized predominantly by technology providers?
34. Is there high financial (investment) risk associated with the implementation of the process?
35. Are there substantial R&D efforts for developing new application areas for the process?
36. Is the equipment downtime relatively low?
37. Is this “Off the shelf” technology?
38. Does the process reach the maximum of its potential commercial impact in terms of revenue generation and/or functionality?

Capabilities

39. Are the process capabilities studied and optimized for structuring various materials?
40. Has an analysis to determine process yield and capability (6s, Cp, Cpk, Cm) been performed?
41. Is the commercial impact of the process (revenue generation and/or functionality) studied and known?
42. Is the process supported by in-line/in-situ measurement system?
43. Does the process deliver predictable and consistent results at different locations?
44. Are the effects of individual process parameters on quality characteristics known?
45. Does the process deliver products of acceptable and consistent quality?
46. Do you think that we are at the early stages of establishing the process capabilities (positive trends in the process development)?
47. Does the process deliver products of good quality conforming to specified standards and requirements?
48. Are the process outcomes predictable if rigorous discipline is applied?
49. Is the work-product/production-run known quantitatively?
50. Does the process deliver precise but still not accurate results due to systematic errors?
51. Does the process show significant improvement in the yield and capabilities (6s, Cp, Cpk, Cm)?
52. Do you consider that analytical modeling/ simulation of the process exists but is not accurately reflecting the actual performance?
53. Do you consider that ONLY relatively accurate correlation between analytical modeling/ simulation and actual process performance is already achieved?
54. Are there well accepted and accurate analytical models for simulating the process?
55. Is the performance of the process optimized to meet current & future business needs?

Fig 6. Questionnaire, subdivided into the three process management categories

4.2 Assessment of Maturity Levels

The proposed methodology was applied also to analyze a set of process pairs that potentially can constitute the building blocks of various process chains. In particular, a maturity assessment of the following eight process pairs and their constituent processes was carried out:

- UV Laser and Projection Mask-Less Ion Beam Patterning (PMLIBP)[44] ;
- Focused Ion Beam (FIB) and Pico Second (PS) Laser ablation;
- E-beam Lithography and Deep Reactive Ion Etching;
- Micro Milling (µMilling) and PS Laser ablation;
- X-ray lithography and Electroforming;
- FIB and Hot Embossing (HE);
- FIB and Micro-injection Moulding (µIM);
- µMilling and HE.

The individual state-of-the-art MNM processes included in these eight pairs are considered viable combinations of technologies within the EUMINAfab infrastructure. To assess the maturity levels of these pairs, experts in respective component technologies were asked:

- to complete the Maturity Assessment Questionnaire for the component processes in these pairs, and also
- to provide the required data to complete the PPMMs for the considered process pairs.

In this way the required data was collected to assess MLs of the considered process pairs. It should be stated that the representativeness of such an analysis is highly dependent on the experts' "unbiased" knowledge of the constituent processes in the pairs.

The first step in implementing the methodology was to generate maturity profiles of the constituent processes across the defined KPCAs based on the collected data and thus to create “snap shots” of their current state of development. Next, the PP_ML of each pair was estimated taking into account the factors affecting it as discussed in Section 3.3. In particular, the maturity level of a process pair (PP_ML(1,2)) could be assessed by accounting for the MLs of its constituent processes (PML_1 and PML_2) and meta-parameters (C_r and C_b). The assessment model is based on the rationale that, the PP_ML increases when:

- the difference in maturity levels ($PML_1 – PML_2$) decreases and is as low as possible;
- the individual maturity levels, PML_1 and PML_2, increase and are as high as possible;
- C_r increases and is as high as possible;
- C_b increases but with a marginal/lower impact in comparison to C_r.

In this pilot implementation, after discussing above interdependences with experts the following formula was adopted:

$$PP\_ML_{(1,2)} = \frac{1}{6}\left[\sum_{KPCA=1}^{6} \frac{\min(PML_1; PML_2)}{1+\left|PML_1 - PML_2\right|} * C_{cw}\right] \quad (3)$$

where C_{cw} is the normalised combined complementarity and compatibility weighted score. C_{cw} should take into account that a higher C_b means that the two processes in a pair while compatible have a marginal added value. For example, the processes can be considered alternative or competing technologies, and thus one of them could be omitted to reduce the complexity of a process chain and thus the risk and costs associated with its implementation. At the same time C_r should have a higher impact on C_{cw} because by combining two complementary processes a higher ‘value-added’ can be gained in a functional and/or economic sense. Therefore, the impact of C_b is marginalized by using the m^{th} root of C_b in the formula for computing C_{cw} while the score increases linearly with the increase of C_r. In this pilot implementation m was set to 10 and thus C_{cw} can increase up to 27% with the increase only of C_b while the impact of C_r on C_{cw} cannot be less than 73% when all KPCPs are mapped as complementary. In particular, the formula for C_{cw} used in this study is as follows.

$$C_{cw} = \frac{C_r + \sqrt[10]{C_b}}{N + \sqrt[10]{N}} \qquad (4)$$

Based on the obtained PMLs and PP_ML values, the pairs and their constituent processes were positioned along a normalized scale, from 0 to 100%, covering all five maturity levels: (1) Initial, 0 to 20%; (2) Repeatable, 20 to 40%; (3) Defined, 40 to 60%; (4) Managed, 60 to 80%; (5) Optimized, 80 to 100%. Based on this ML assessment, it was possible to conduct:

- a comparison of MLs of the processes in regards to the three process management categories;
- a comparison of MLs of constituent processes in the pairs in regards to their KPCAs;
- the identification of strengths and weaknesses associated with the process pairs taking into account the current state of their constituent processes;
- an assessment of the complementarity and compatibility of technologies with regards to their respective KPCAs.

5. Discussion of Results

MLs of the process pairs and their constituent processes considered in this pilot implementation of the methodology are reported and discussed hereunder to illustrate its analytical potential. Fig.7 presents MLs of the analysed component technologies across the three process management categories. Then, figures 8 to 15 below present the overall MLs and the ML profiles across the six KPCAs for the considered pairs and their constituent processes.

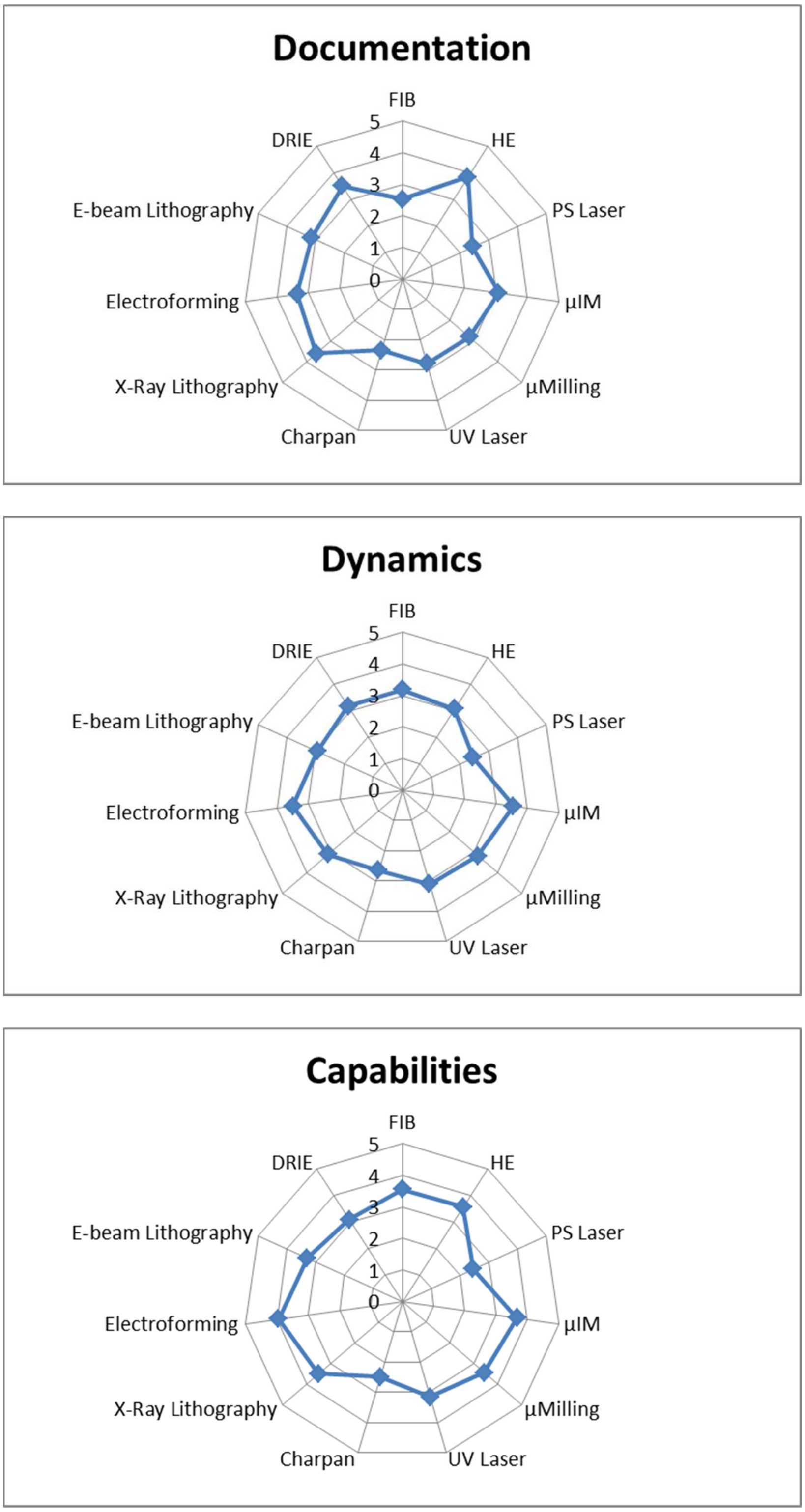
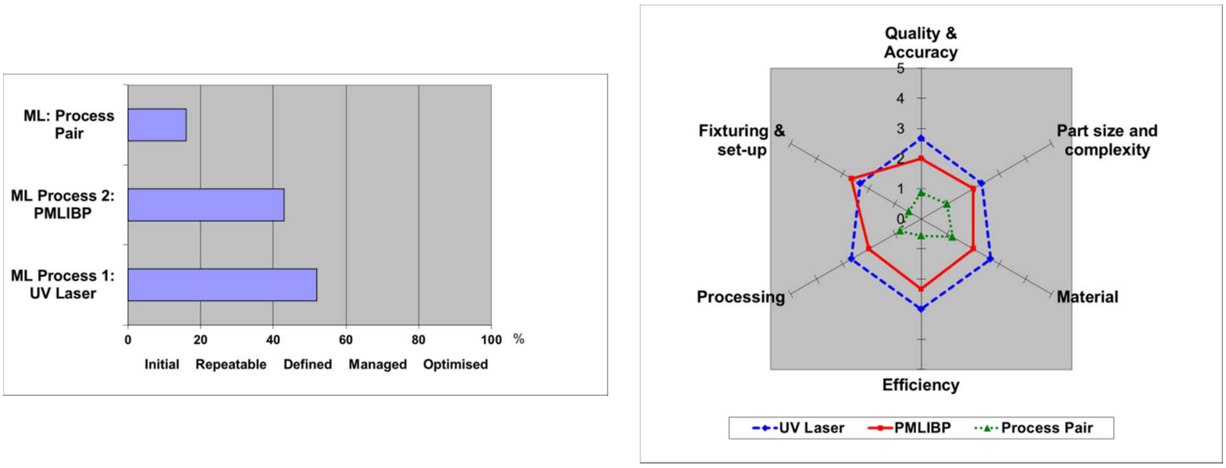


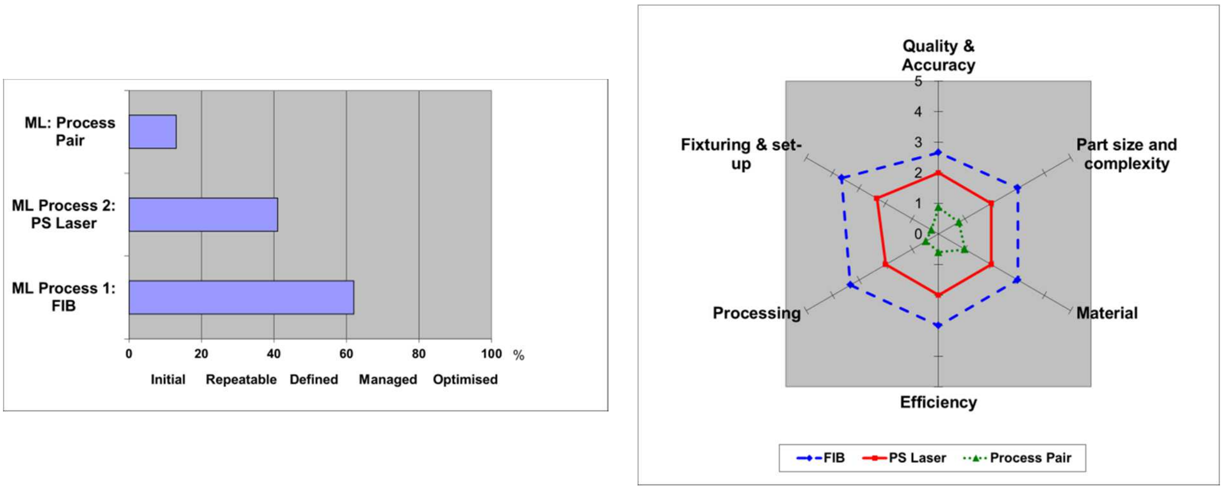
Fig 7. Maturity Levels of component technologies across the three Process Management Categories



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

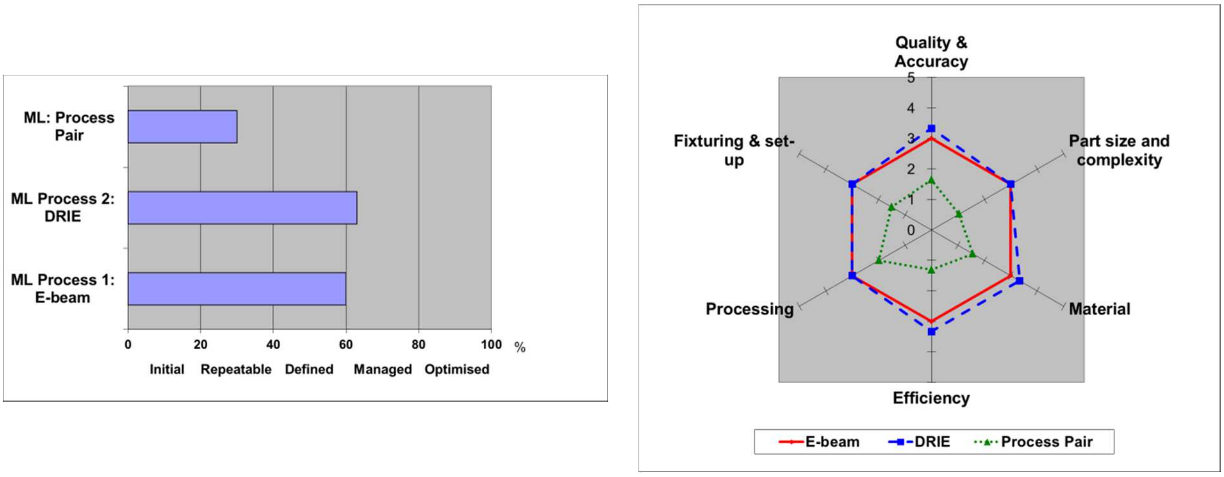
Fig. 8 UV Laser and Projection Mask-Less Ion Beam Patterning



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

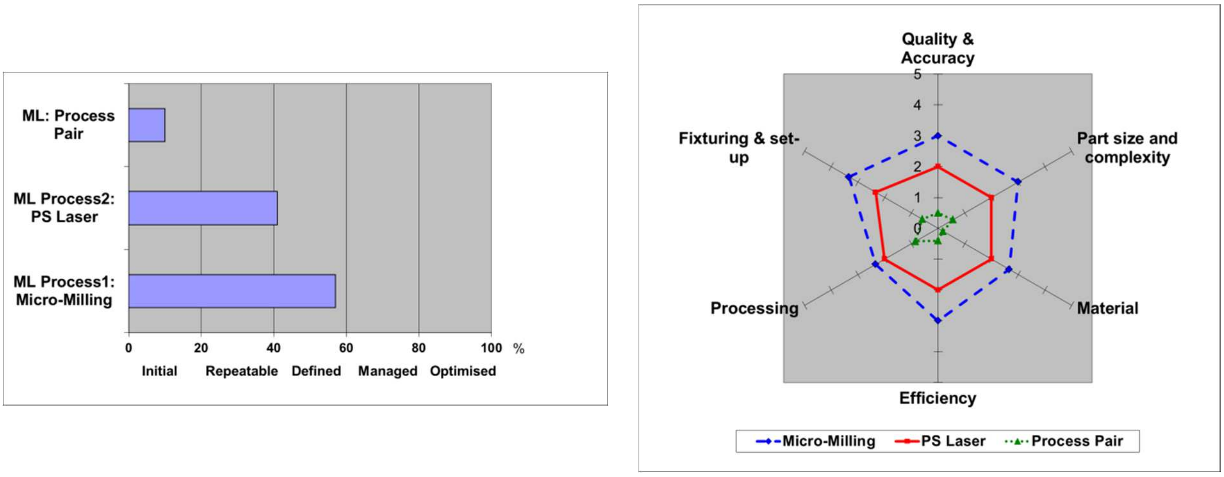
Fig. 9 FIB and PS Laser ablation



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

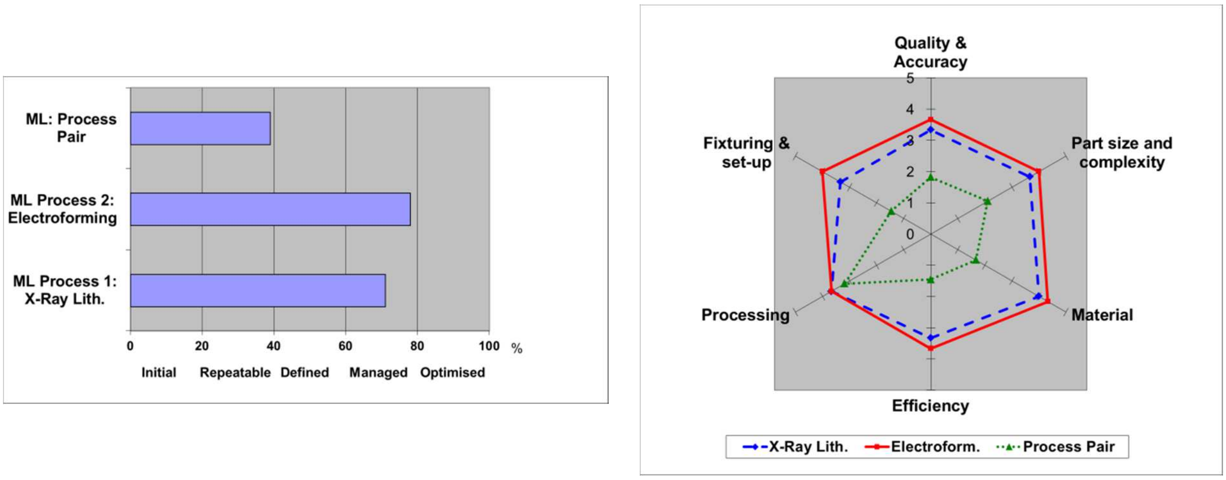
Fig. 10 E-beam Lithography and Deep Reactive Ion Etching



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

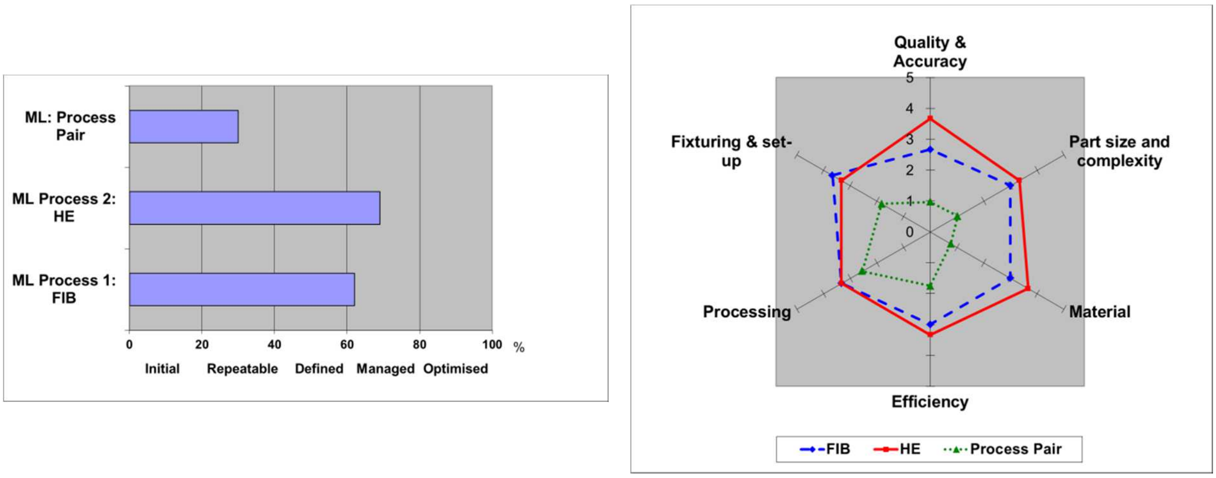
Fig. 11 Micro Milling and Pico Second Laser ablation



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

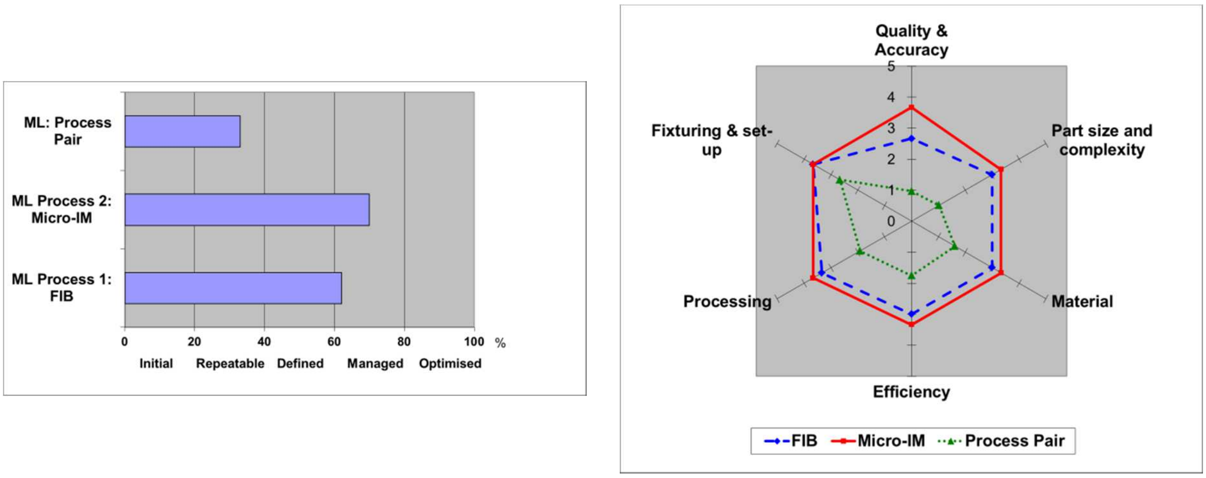
Fig. 12 X-ray lithography and Electroforming



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

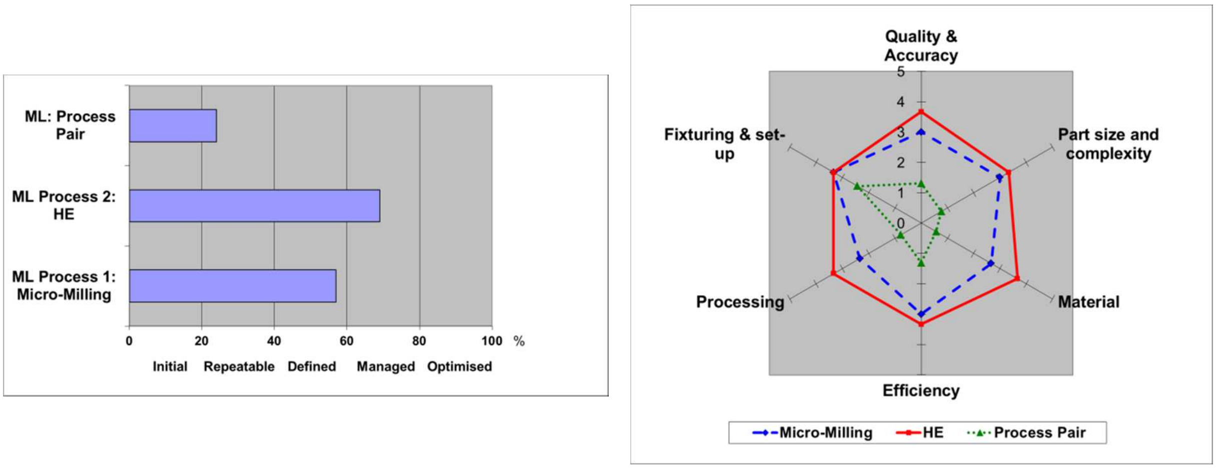
Fig. 13 FIB and Hot Embossing



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

Fig. 14 FIB and Micro-injection Moulding



a) Overall MLs of the pair and its constituent processes

b) KPCA chart of the pair and its constituent processes

Fig. 15 Micromilling and Hot Embossing

5.1 Component Technology Maturity Levels across the Process Management Categories

Analyzing the component technologies in Fig. 7, it can be observed that:

- Any similarities in MLs are reflected in the scale of differentiation between the component technologies' values across the three Process Management Categories. In particular, the Dynamics radar chart depicts less differentiation and thus indicates that the processes are quite similar in their maturity in regards to this process management category.
- Studying the radar chart for the Documentation category, it can be observed that ML of the MNM processes show a higher differentiation and the MLs vary from 'Repeatable' to 'Managed'. HE has the highest ML, whilst PS-Laser and Projection Maskless Ion Beam Patterning (PMLIBP) have the lowest value.
- With regards to the Capabilities radar chart of the considered MNM component technologies the ML are not consistent and they again vary from 'Repeatable' to 'Managed'. The capabilities of Electroforming are judged to be the most validated in comparison with other processes whilst again PS-Laser and PMLIBP are the most underdeveloped.
- In all three categories (Documentation, Dynamics and Capabilities), the overall status of the PMLIBP technology is due to the novelty of the process which is only existing as a proof-of-concept tool. Thus, this process is under development to fulfil the industry's need for a high productivity, flexible and cost-effective structuring technology for large (i.e. over 6 inch) surfaces with a resolution better than 10 nm.

5.2 KPCA Charts

The results of the analysis of the ML profiles in Figures 8b to 15b across the six KPCAs of the pairs and their constituent processes are shown in Table 3. In particular, the table depicts the results for the constituent processes on the left and for the pairs to the right, in terms of their overall ML, profiles' consistency and MLs across the 6 KPCAs. At the process level, the MLs of the 6 KPCAs are compared to each other, while the pairs' KPCAs are judged in regards to the average PP KPCA ML taking into account the specific KPCA's compatibility and complementarity scores. Furthermore, the pairs' overall compatibility and complementarity scores provide another assessment of the constituent processes' suitability for combining them into pairs. Thus the table shows clearly the strengths and weaknesses of the process pairs whilst taking into account the perceived current capabilities of their constituent processes. For example, taking the UV laser + PMLIBP pair, it can be stated for the component processes that the UV laser process has ML 3 while it is borderline between ML 2 and ML 3 for the PMLIBP process. At the same time their capability hexagons are quite symmetrical. With the exception of "Fixturing & set up", the MLs of all the UV laser KPCAs are higher than those for PMLIBP. At the same time, as the pair's MLs are highly dependent on the consistency and magnitude of the constituent process MLs, the magnitude of the difference between the MLs and the compatibility and complementarity scores across all KPCAs (the capability hexagons' symmetricity), the pair has a low ML of 1. It can also be observed that the pair's "Fixturing and Set-up" and "Efficiency" KPCAs have low MLs due to the fact that the considered KPCPs, are predominantly more compatible rather than complimentary. Furthermore, overall the KPCPs of the constituent processes are only marginally more complimentary than compatible. Collectively, the results show that these two processes are alternatives rather than a process sequence that can lead to added-value and thus to broaden the pair's capabilities.

A similar analysis of the other pairs can be conducted based on the results in Table 3 and thus to make conclusions about their strengths and weaknesses.

Table 3 Assessment of the KPCA maturity profiles of the pairs and their constituent processes

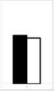
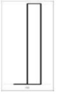
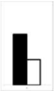
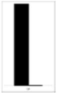
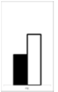
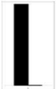
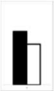
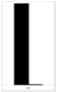
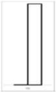
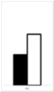
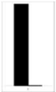
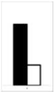
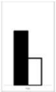
Process Pair	(i) Comparison of constituent processes								(ii) Analysis of process pairs									
	ML	ML Profile	KPCAs						ML	ML Profile	KPCAs						Overall KPCP Cr/Cb Score	Potential as a pair (Y/N)
			Quality and Accuracy	Part Size & Complexity	Material	Efficiency	Processing	Fixturing & Set-up			Quality and Accuracy	Part Size & Complexity	Material	Efficiency	Processing	Fixturing & Set-up		
UV Laser	❸	◘	+ +	+	+ +	+ +	+ +	-	❶	□	≈	↑	↑↑	↓	≈	↓↓		**N**
PMLIBP	❷|	◘	- -	-	- -	- -	- -	+										
FIB	❸|	◘	- -	-	- -	-	o	+	❷	□	↓	↓	↓↓	↑	↑↑	↑		**Y**
HE	❹	■	+ +	+	+ +	+	o	-										
FIB	❸|	◘	+ +	+ +	+ +	+ +	+ +	+ +	❶	□	↑	↑	↑↑	≈	↓	↓↓		**Y**
PS Laser	❷|	■	- -	- -	- -	- -	- -	- -										
FIB	❸|	◘	- -	-	-	-	-	o	❷	□	↓↓	↓↓	≈	≈	↑	↑↑		**Y**
µIM	❹	■	+ +	+	+	+	+	o										

Table 3 Assessment of the KPCA maturity profiles of the pairs and their constituent processes

Process Pair	(i) Comparison of constituent processes								(ii) Analysis of process pairs									
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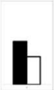
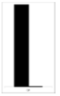
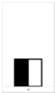
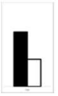
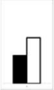
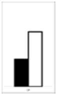
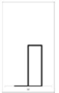
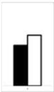
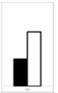
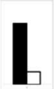
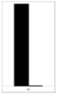
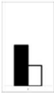
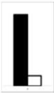
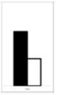
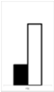
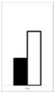
			Quality and Accuracy	Part Size & Complexity	Material	Efficiency	Processing	Fixturing & Set-up			Quality and Accuracy	Part Size & Complexity	Material	Efficiency	Processing	Fixturing & Set-up		
µMilling	❸	◘	- -	-	- -	-	- -	o	❷	□	↑	↓	↓↓	↑	↓	↑↑		**Y**
HE	❹	■	+ +	+	+ +	+	+ +	o										
µMilling	❸	◘	+ +	+ +	+ +	+ +	+	+ +	❶	□	≈	≈	↓↓	↓	↑↑	↑		**N**
PS Laser	❷|	■	- -	- -	- -	- -	-	- -										
X-Ray Lith.	❹	◘	-	-	-	-	o	- -	❷	□	≈	↑	≈	↓	↑↑	↓		**Y**
Electroform	❹	◘	+	+	+	+	o	+ +										
E-Beam	❸	■	-	o	-	-	o	o	❷	□	↑	↓↓	≈	↓	↑↑	≈		**Y**
DRIE	❸|	■	+	o	+	+	o	o										

<table>
<tr><td colspan="3">Key:</td><td rowspan="4">Cr Level</td><td rowspan="4">Cb Level</td></tr>
<tr><td>Symmetrical: ■</td><td>Quasi-symmetrical: ◘</td><td>Asymmetrical: ☐</td></tr>
<tr><td colspan="2">- - = much worse; - = worse; o = same ; + = better; ++ = much better in comparison to the other process in the pair</td><td>N = No, Y = Yes</td></tr>
<tr><td colspan="2">↓↓ = significantly lower ; ↓ = lower; ≈ = similar (close to); ↑ =higher; ↑↑= significantly higher in regards to the average PP KPCA ML.</td><td>MLs: ❶❷❸❹❺</td></tr>
<tr><td colspan="5">I = Borderline case between depicted ML value and next higher ML, e.g. ❷I is a borderline ML between ML 2 and ML 3</td></tr>
</table>

5.3 Overall Maturity Levels

The overall MLs of the analyzed MNM technologies and their pairs are shown in Figures 8a to 15a and Table 3. Thus, the range of MLs of the individual technologies is from Level 2, ‘Repeatable’, to Level 4, ‘Managed’, whilst that of the pairs is from Level 1, ‘Initial’ to Level 2, ‘Repeatable’. The results were discussed with the experts in MNM and it was concluded that they reflect adequately the perceived current MLs of the considered processes and their pairs.

Looking at MLs of the processes, it is not surprising that μMilling is considered a ‘Defined’ process, ML 3 (57%) , taking into consideration that: (i) a lot of R&D effort was put in its development in recent years, (ii) the technology is currently being exploited commercially by mould and watch making industries, whilst at the same time, (iii) the research community recognizes that further fundamental investigations are still needed to understand and especially to model the machining mechanics at micro scale[45,46]. Also, μMilling is ranked higher than PS laser ablation and this reflects well the industrial impact of these technologies in context of their use as master-making processes. PS laser ablation is considered as a borderline case between a ‘Repeatable’ process, ML 2, and a “Defined” process, ML 3, (41%) in spite of the fact that it is currently commercially exploited and significant R&D efforts are put in its development (Wu & Ozel, 2011). However it is generally accepted that various open issues remain with respect to: the modeling & simulation of PS laser-material interactions[47,48]; the empirical character of the process optimization; the predictability of the process performance; and the necessity for further optimization of material removal strategies[49] .

Both X-Ray lithography and Electroforming were judged to be ‘Managed’ processes, ML 4 having normalized values of 71% and 78% respectively. This result was considered representative by the MNM experts and is also supported by the fact that significant efforts have been placed in the development of these technologies. Furthermore, both processes have been studied extensively in the development of the LIGA process chain that has been widely used to fabricate MEMS, MOEMS and microfluidic devices[50–52] . In addition, it should also be noted that X-ray Lithography “is still being used as a mature lithography technology for small batch production of VLSI and other micro and nano technology application areas”[50].

E-beam was judged to be ‘Defined’ process, ML 3 (60%), whilst DRIE with a normalized value of 63% is considered as a borderline case between a “Defined process”, ML3 and a “Managed” process, ML 4.These results seems to be on the conservative side when taking into account their application areas and the significant investment in the development of these technologies. In particular, both E-beam lithography and DRIE, have been used in process chains for mass production of ICs and also MEMs[50,53] whilst DRIE has also been utilised to fabricate silicon based tooling for hot embossing and micro-injection moulding processes[50] . Furthermore, in the last decade, substantial work was carried out to improve the performance of these two technologies[50,54] .

The FIB process has a normalised maturity level value of 62% and thus is also considered as a borderline case between a “Defined process”, ML 3, and a “Managed” process, ML 4. Again this appears to be a realistic judgement when one considers the technology advances in the last two decades to make it an important MNM tool and an indispensable technology in semiconductor IC manufacturing and R&D[50,55] . In particular, recent promising research work concerning the optimisation of the FIB milling process for micromachining applications[56–58] and the use of the FIB milling process to manufacture replication cavities in various materials[7,59–61] has also been published.

Both replication processes, namely HE and µIM were judged to be ‘Managed’ processes, ML 4 with normalized values of 69% and 70% respectively. These results were judged again representative by the experts and are also supported by the facts that (i) substantial efforts have been aimed at the development of these technologies over the years, and (ii) these processes are utilized by industry successfully for serial production of polymer micro parts in a range of application areas, such as micro/nano optics, precision micromechanics, micro/nano-fluidics, and CD/DVD replication[13,52,62–67] .

Finally, a close look at MLs of the UV-Laser and PMLIBP processes reveals that PMLIBP is a borderline case residing between a ‘Repeatable’ process, ML 2, and a “Defined” process, ML 3, (43%) and thus has an equivalent ranking to that of PS-Laser. However, this result should be taken with a certain amount of precaution given that it is based on the experience with only one pilot installation, and thus it is considered premature to judge about the PMLIBP maturity. In contrast, ML 3 (52%) for the UV laser appears to be a conservative judgment when considering its broad use for direct writing or mask based patterning [50,68–76]. Furthermore, it was successfully integrated with other technologies, such as electroforming, µIM and HE, into a LIGA-like process chain called Laser LIGA[50,68,73]. Finally, from an application point of view, it was also demonstrated that UV Lasers are suitable to fabricate microstructures for applications in microfluidics, micro-optics and biomedical devices[69–71,73,74].

5.4 Methodology

The analysis of the results and an evaluation of the proposed methodology revealed both strengths and weaknesses in its implementation.

Strengths:

1) The proposed methodology can be used to unify the maturity assessments of process chains by taking into consideration their constituent manufacturing technologies and by paying special attention to their interfaces through their input-output relationships.

2) The qualitative and quantitative data used for the process pairs and their constituent technologies can be considered representative because they are obtained from experienced process experts.

3) The results provide a valuable insight into the current state of manufacturing technologies and their potential integration into new process chains, and thus to assist in their design and selection taking into account the requirements for any given product.

4) It utilises an expert-based qualitative framework to determine MLs and the results obtained were judged as representative and also reflected well the current state in the development of any given technology.

5) It reveals the ‘weaknesses’ and ‘strengths’ of these technologies and their respective process pairs, and thus to make an informed judgment about any open issues on which to focus in their development.

6) It provides ML “snapshots” that can be utilized in follow up studies to judge about the technology advances over given time periods.

7) The methodology can be applied to identify suitable process pairs or their variations in regards to specific product requirements, and ultimately it could be used as a knowledge base for developing new manufacturing solutions. At the same time, it can highlight some open issues associated with process pair/process chains and their constituent technologies.

8) The methodology can be applied to assess not only the manufacturing processes but also systems/equipment for inspection and materials’ characterization however it is necessary to modify the maturity indicators accordingly.

Limitations

9) The input of the experts consulted can be biased to given equipment and machines and their specific applications and thus the results may not be sufficiently generic and representative for the capabilities of any particular technology. This could explain the MLs of E-Beam, DRIE and UV laser processes obtained in the methodology’s pilot implementation that were on the conservative side. A possible way to address this issue is to rely on a bigger pool of experts.

10) The pilot implementation of the methodology relied on an input from face-to-face type

questionnaires that limits the number of the consulted experts. Other techniques such as a self-administered on-line or mail questionnaires can also considered for possible future implementations of the proposed methodology[43].

11) The methodology can be used for assessing process pairs and their constituent technologies however further development is necessary to apply it for assessing more complex process chains.

12) It will be beneficial if the proposed expert-based approach can be complemented by empirical assessments of processes and process chains' maturity, e.g. by conducting Round Robin tests. The results from such research should also be used to find a more evidence-based way for combining complementarity and compatibility scores of pairs.

13) Although the experts in MNM concluded that the ML values of the considered pairs reflect adequately their perceived current level of development and industrial impact, a ML 2 for the X-Ray Lithography + Electroforming pair seems to be somewhat on the conservative side taking into consideration that both technologies have been applied successfully in the LIGA process chain. This result can be attributed to the formula used to calculate the pair's MLs and thus it is necessary to look at and improve it to reflect better the perceived ML of the pairs.

14) The methodology does not adequately take into consideration all implementation related risks. Mankins[21] states that the maturity of the technology correlates with the technical risks and thus the proposed approach has to be improved further to factor uncertainties associated with the design and implementation of multi-process manufacturing platforms.

6. Conclusions

The work reported in this paper aims at reducing the risks associated with the adoption and integration of manufacturing technologies, e.g. MNM processes, into process chains underpinning existing and emerging miniaturized products. It presents a new instrument for assessing technology maturity of processes and process pairs which: (i) utilizes an approach for modelling output-input dependences of pairs' constituent processes and, (ii) is inspired by a capability maturity model that was applied successfully in the software engineering domain. The main characteristics of the proposed approach for maturity assessment are:

- The methodology provides a systematic and effective way to analyze the interfaces between manufacturing technologies in pairs and process chains and thus to assess their respective input-output complementarity and compatibility.
- It aims to study the maturity of process pairs, and thus to assess the risks associated with their implementation.

The proposed methodology was tested on eight MNM process pairs to judge about their overall maturity and also about their respective Key Process Capability Areas. The results demonstrate the applicability of the proposed methodology as a means to evaluate the maturity of the MNM pairs and their constituent processes. In addition, it can be stated that this methodology can be employed in the design of new process chains by identifying suitable pairs, and also as a tool to identify weaknesses in pairs related to their KPCAs. The benefits from and advantages of the proposed methodology can be summarized as follows:

- It provides a comprehensive framework for assessing the maturity of processes and process pairs by modeling the interfaces between the component technologies.
- The rationale behind the proposed framework is easy to understand, and it is a systematic and structured approach for conducting studies to determine MLs of individual processes and process pairs
- The methodology utilizes inputs from process experts to assess the maturity of manufacturing processes.
- The ML results can be expressed as: (a) overall values or (b) hexagons across the six KPCAs or (c) polygons for each process management category.

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