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RESEARCH

Application of innovation theory to metal forming modelling: FEM sunset and AI dawn??

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Abstract
The paper derives from a simple question that the authors have asked themselves when attending conferences and reading articles on modelling of metal forming processes: is numerical modelling based on FEA still innovative? Are the proposed results able to provide a further effective enhancement to scientific knowledge? And how huge was the effort to obtain such an eventual enhancement? Starting with these questions, the authors applied some basic concepts of Innovation Theory to the last forty years of numerical modelling of forming processes and understood that this technology has reached its natural limit: only small enhancements of modelling performances are obtained despite quite big efforts. Also, research topic trends analysis was performed within ESAFORM community through text mining approaches. Now, to answer the research questions still open, a disruptive discontinuity is necessary, aimed at assessing a new master modelling technology.

Keywords Innovation theory · Numerical simulation · Esaform · AI · FEM

Introduction

In the last three or four decades, numerical modelling has represented a must for researchers operating in the field of metal forming. It would be very hard to find even a single researcher who has not encountered a finite element code or has not carried out a numerical simulation during his or her research activity. Starting from the very beginning of the 70ies, Finite Element modelling has demonstrated clear advantages in comparison to former methods (slab-method, upper-bound method, slip lines and so on), to investigate process mechanics and to predict not only forming loads, but also stresses, strains, temperatures, damage and so on. This is the main reason of such a success and even an incomplete list of papers focused on numerical modelling of metal forming processes would fill several volumes.

But, nowadays, is current research on numerical modelling of metal forming processes really innovative? Or, alternatively, are we observing a prolonged and gradual progression of minor, incremental enhancements, each offering only a modest amount of innovation?

To answer these questions, this paper is focused on the analysis the evolution over time of numerical modelling as modelling technique, utilizing some concepts and ideas of Innovation Theory. For a very long period numerical modelling has been the master modelling technique, but nowadays it is approaching its own natural limit in particular as far as complex material modelling (damage, recrystallization, other metallurgical phenomena) is concerned. Overall, the use of numerical modelling as a broad and robust design tool, even when combined with optimization methods, is revealing significant limitations.

According to Innovation Theory, once the former master technique has reached its natural limit, a new age of competition (and turbulence) is going to start to assess the new dominant technique. The potentials of Artificial Intelligence and Machine Learning seem very promising, but the competition is still open!

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The above conclusions have been obtained retracing forty years of numerical modelling of metal forming processes; as a case study, numerical modelling of one of the most interesting sheets forming processes, namely SPIF has been investigated with larger detail. Furthermore, a wide analysis of the recent scientific literature has been carried out, both using coding and artificial intelligence, to highlight which are the most diffused trends and confirm our assessments.

Some remarks on innovation theory

First, some principles of Innovation Theory must be assessed. The basic assumption is that both the rate of improvement in the performance of a technology (in the case a modelling technique is investigated) and its diffusion rate among researchers, follow an S-curve trend [1].

Figure 1 shows that at the beginning a large effort is necessary to get even small improvements (learning time) because the basic principles of the technology are not yet completely understood. Then a virtuous phase with a steep growth of the performances occurs, due to the full understanding of the technique, to the increase of researchers involved in such research and to the interest of developers to make the modelling tool always more powerful. But, after some time and a lot of effort, the technology achieves its own natural limit: this is clear because even big efforts produce quite limited incremental enhancements in the performance.

Not always techniques achieve their natural limit, because they could be replaced by the success of a new disruptive and discontinuous technique, able to replace the former one due to indisputable advantages. In the meantime, researchers may be reluctant to adopt a new technique due to relevant effort spent in the existing ones but could be forced to do it if their improvements become too slow and expensive.

The diffusion rate of a technology (a modelling technique) among the researchers also follows an S-curve. At the beginning, when a new technique is proposed, its adoption is slow. As soon as users acquire a deeper knowledge of the technique and understand the related potentiality, adoption rate increases. In other words, the diffusion of a Modelling Technique strongly depends on the development and the dissemination of the related knowledge base, sometimes very complex.

It is worth pointing out that, understanding, diffusion and development of performances are strongly affected by a couple of issues, mutually influencing:

- the dimension of the user's base (in our case, the base of the involved researchers);
- the availability of the so named complementary resources (Hardware, I/O Facilities, remeshing algorithms, new models, computing power and so on).

Figure 2 shows that such a mechanism can be described as a virtuous cycle arises [2]: a larger user's base attracts complementary resources producers, and, in turn, the availability of complementary resources attracts new researchers. In other words, more are the users, the greater is the interest of developers to enter in the market, providing new tools that, in turn, may attract new users.

The above considerations well justify the above discussed virtuous phase with a steep growth of the technology performances.

But, after some time, the technology reaches its own natural limit and could be no more able to increase its performance despite a very big effort by the researchers. Only quite small incremental enhancements are possible, even with a lot of time and money spent in the work. When the natural limit of the current master technology is reached,

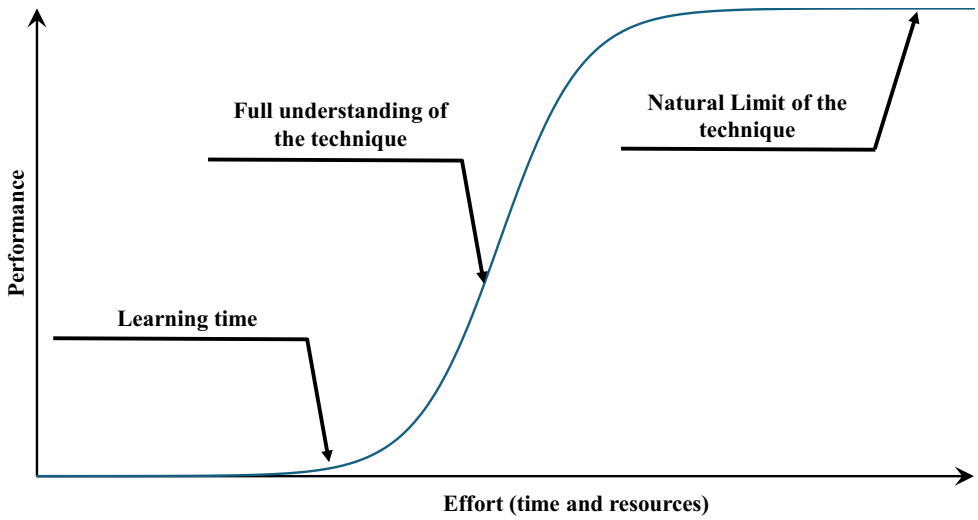


Fig. 1 Traditional S-curve for describing the lifetime evolution of a technology [1]

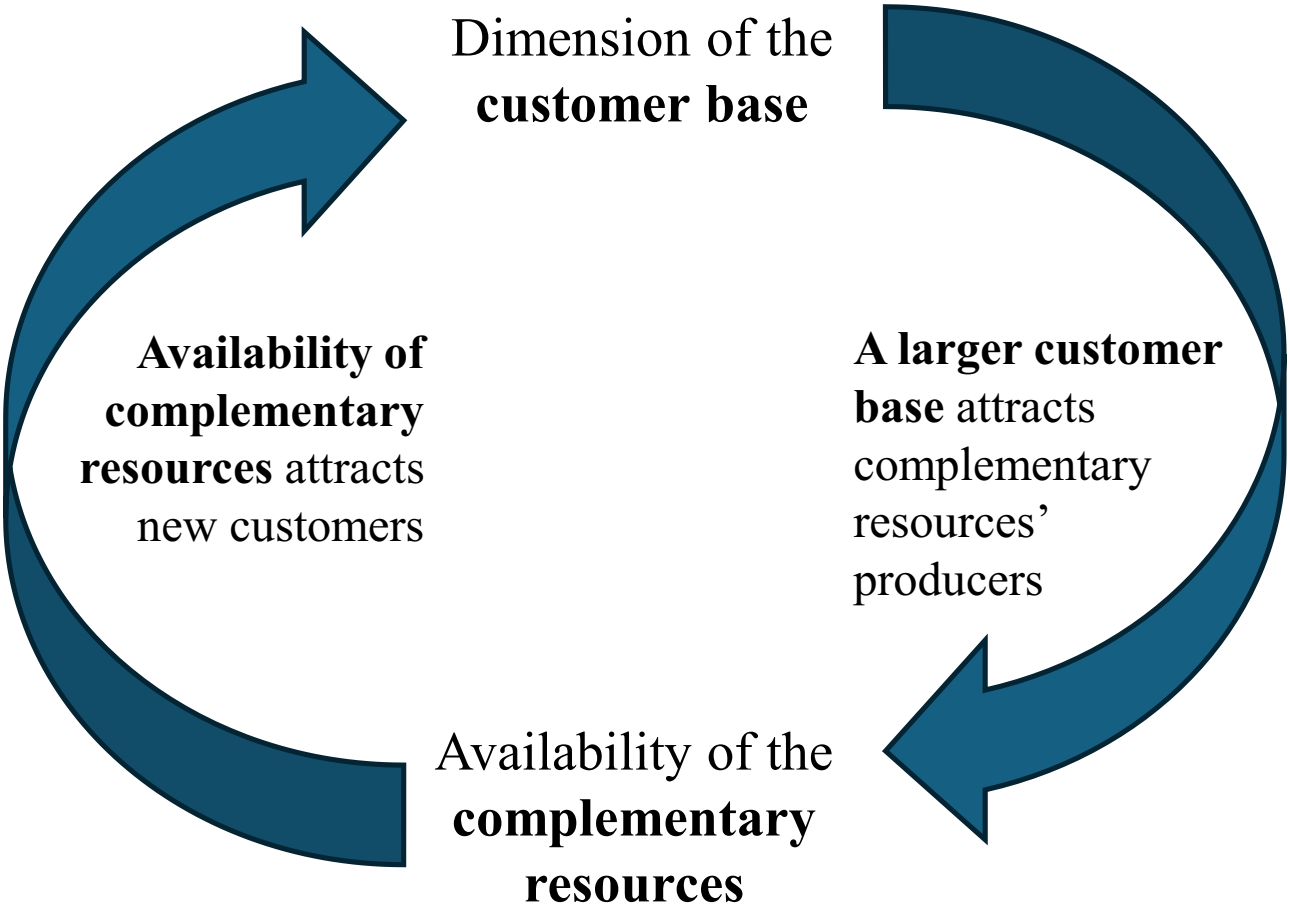


Fig. 2 Virtuous cycle describing the adoption rate of a technology

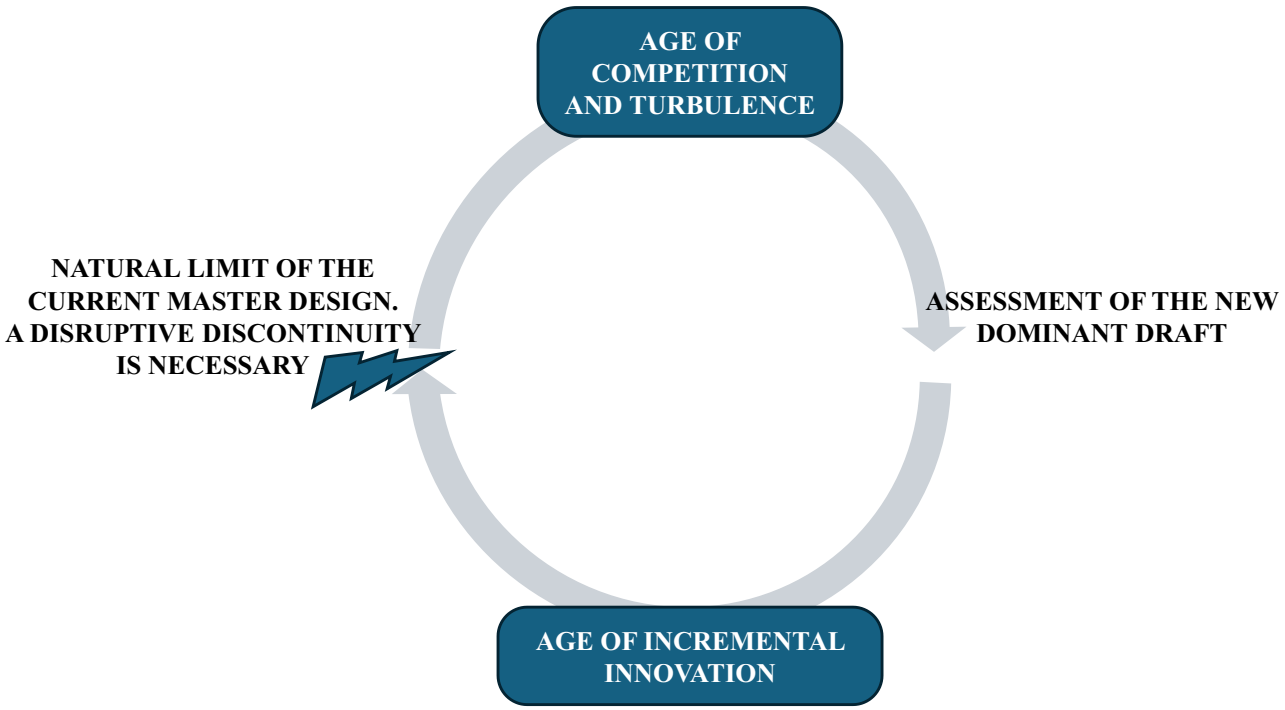


Fig. 3 Disruptive cycle from the age of competition to the age of innovation

a disruptive discontinuity is necessary [3]. Figure 3 shows that a fierce competition among potential alternative starts and an age of turbulence and competition arises, up to the new technology wins, affirm itself as master technology, and again, a new age of virtuous incremental innovation starts [4].

Application of innovation theory to numerical modelling of metal forming processes

Let's apply these concepts to the evolution of numerical modelling of metal forming processes in the last 40 years. Figure 4 attempts to provide graphical evidence of this evolution.

Up to the end of the sixties, the most diffused modelling techniques were the Slab Method [5], the Slip Lines Method [6] and the Upper Bound Method [7, 8].

Despite the wideness of their diffusion all over the world, they had several limitations: heavy simplifying hypotheses were necessary, limiting their effectiveness only to basic processes, and what is more, they were able to predict with satisfactory precision the forming loads, but could not understand process mechanics. Using these methods, material flow, stress and strain distributions could be calculated only for very simple and basic metal forming processes.

During the 70's, two fundamental milestones must be highlighted: the paper from Lee and Kobayashi [9], who proposed for the first time in 1973 a new solution to rigid-plastic deformation problems and the world known basic textbook by O.C. Zinkewicz [10]: therefore it can be can assumed that these years are just the beginning of the learning phase, when the new modelling technique is proposed, starts to show some potential advantages, but its effectiveness to investigate real metal forming processes hat yet to be demonstrated.

At the beginning of the 80's, FEA was able to approach simple steady-state 2-D problems with no remeshing [11], while at the middle of the decade the former remeshing applications [12], as well as the former 3-D analyses with no remeshing were proposed [13]. At the end of the 80's, it is possible to assess the numerical modelling is a well-established technique to investigate industrial 2-D problems (either steady-state and no steady-state) [14]: several developers had already entered in the marked and powerful commercial codes were available. Therefore, it can be assumed that late 80's corresponds to the end of the learning phase and the beginning of the virtuous phase with a steep growth of the performances.

The following two decades, in fact, really were a sort of "explosion" of the performances of numerical modelling, due to the virtuous cycle between the growth of the researcher's base and the continuous development of new

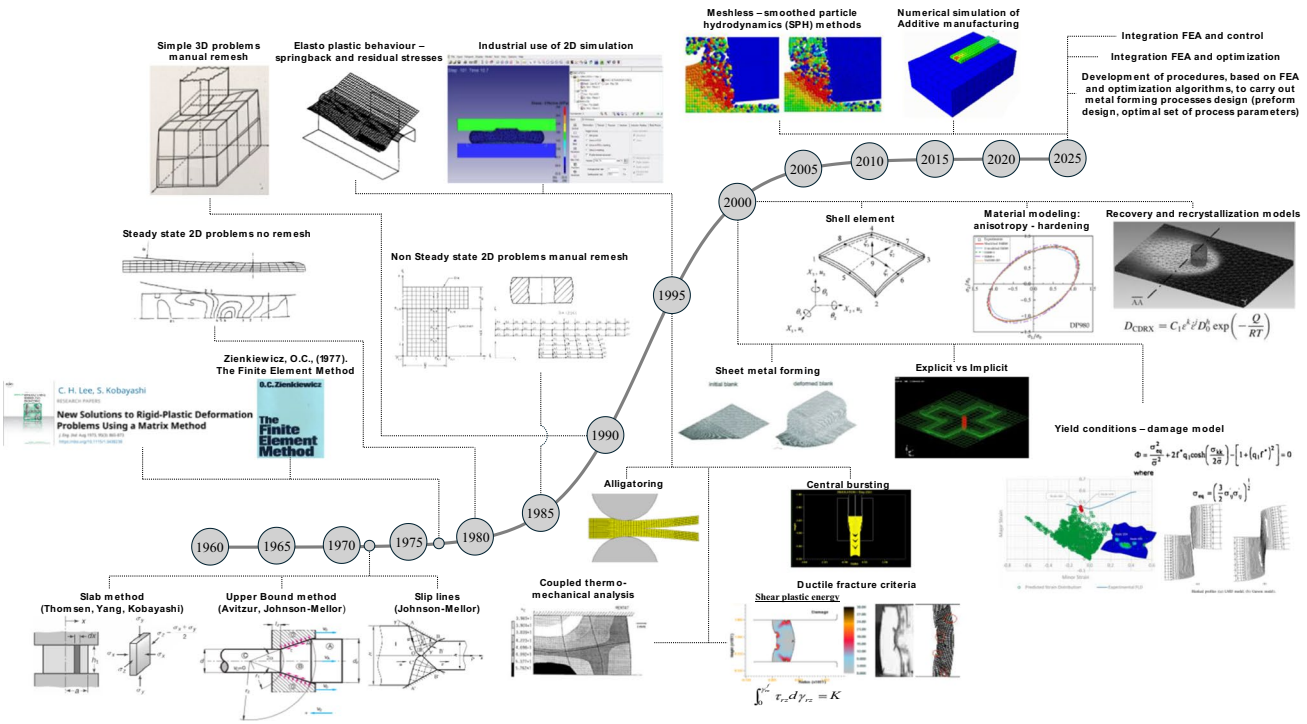


Fig. 4 S-curve of the finite element method approaches

complementary goods, I/O facilities, models, computing power, remeshing algorithms. A wide number of developers and companies entered in the marked and provided always more powerful tools.

Considering bulk forming processes, contact conditions at the tool-workpiece interface were modelled including friction and heat transfer. A fully coupled thermo-mechanical analysis became possible, considering heat generation due to plastic deformation and heat transfer [15] and therefore the prediction of forming temperatures as well. Elastic-plastic behaviour was included in the analysis and permitted to calculate elastic springback and residual stresses [16].

Ductile fracture criteria were introduced, opening a new frontier, namely the prediction of forming limits [17, 18]: typical forming defects [19], such as central bursting in extrusion and drawing [20, 21] and alligatoring in rolling were predicted. But also, it became possible to model blanking and fine blanking processes [22].

As well, numerical modelling was applied to sheet forming processes, either utilizing implicit and explicit models during the 90's. Shell element was developed [23] and, in the meantime, new models were developed to consider anisotropy and hardening through the implementation of new effective yield loci and different hardening models [24]. Both required new material testing procedures.

Even for sheet metal forming, process limits were investigated, either utilizing FLC [25] and developing yield conditions able to consider damage [26]: material characterization became more complex, but effective predictions were possible.

In the first decade of the new century, a wide interest to model metallurgical phenomena associated to metal forming processes can be observed, enhancing, once again, the performance of numerical modelling. Recovery, dynamic recrystallization [27], phase transformations [28] were modelled, finally arriving to the so-named tri-coupled analysis [29]: deformation, heat generation and transfer, phase transformation, including complex phenomena such as transformation plasticity, stresses and temperature induced transformations, latent heat. Material behaviour is modelled through very complex models, although parameter calibration becomes very complex and sometimes unstable.

Twenty years of remarkable advances in the performance of numerical modelling, undoubtedly leading technology for investigating metal forming processes!

In the very last years, two major trends can be observed: (i) the proposal of new numerical methods, such as the well-known meshless method [30] and the smoothed particle hydrodynamics (SPH) method [31], to model specific complex processes; (ii) the development of procedures, based on the integration of FEA and optimization algorithms, to move from the "simple" analysis of the process mechanics to the design of the forming process (preform design, optimal set of process parameters) [32, 33].

Despite an impressive number of attempts and effort, the integration between numerical modelling and optimization techniques is showing large limits for providing general, wide and powerful tools in process design. As well, the models utilized to predict complex phenomena such as damage, recovery, recrystallization, phase transformation are really very difficult to be implemented [34], because they require a too difficult and sometimes unstable material characterization, limiting the robustness of the approach.

These considerations allow us to assess that numerical modelling has reached its natural limit, in particular as far as its effectiveness as control and design tool is concerned. Disruptive discontinuity is therefore necessary!

An age of competition and turbulence has already started to establish the new, more effective, master technique to overcome the mentioned problems, maybe after a period of competition among possible alternatives.

Now, AI techniques and, more in particular, Machine Learning seem the most suitable opportunities, although their application to metal forming processes is not so straightforward as in other cases.

AI (and ML) learns directly from data and therefore are based on large data sets. In metal forming large data sets (particularly concerning local information) are difficult to generate in-situ and this is an essential point. Nevertheless, the CIRP Keynote paper by J. Cao et al. [35], collects a huge number of applications, which, up to now, concern:

- Process simulation – material constitutive behavior, failure prediction, forming limits, interface modeling.
- Process control – sensing, data reduction, controllers built on models established on neural networks.
- Process design (process parameters design, tool and preform design, planning problems in metal forming).

We could assume that the virtuous phase has already started!

Application of innovation theory to single point incremental forming

In the previous section the evolution of performance of numerical modelling was analyzed considering metal forming as a whole. Now a particular case is analyzed, namely a specific metal forming process.

In this respect, the Singe Point Incremental Forming (SPIF) was selected. SPIF, in fact, is a relatively new and promising forming process, which strongly needs a general and effective design tool. Specifically, it is a well-known manufacturing process that caught the attention of a large numbers of research centers; it still has some unaddressed

design issues and, its numerical modeling is quite challenging as its process mechanics is quite different from other sheet metal forming processes. Therefore, the authors believe that it is particularly suitable to highlight the limits of numerical modelling.

Figure 5 provides a graphical description of the evolution of numerical modelling of SPIF, taking into account contribution by several researches and research centers all around the world and more in general, the forming community.

SPIF process was first patented by Leszak in 1967 [36]. It is a sheet metal component manufacturing process where a part formed in a stepwise manner by a very simple and universal tool (a cylinder with and hemispherical shape); the component shape is provided by the tool path that is controlled by a CNC system. The sheet is clamped (no material flow is enabled) in a very simple set- up and stretching is the main occurring process mechanics. Overall, SPIF is what manufacturing scientists had dreamt of for decades: a very flexible process that does not require dedicated tooling to form a component, resulting in reduced tooling cost and lead time.

After 1967, learning time for SPIF lasted almost 30 years, in fact the process caught the attention of much research in the 90s. At that time, the interest and research around SPIF process took off and it became a very fertile and dynamic research topic. The interest around the process was mainly due to two reasons: 1/the breakthrough nature of the process that for the first time cut the dependence between the die and the shape to be manufactured; 2/the possibility to carry out the process on any general-purpose milling machine: therefore, almost any lab around the world was equipped with the needed machine to perform SPIF.

Following the Innovation Theory concepts, it is possible to assume that the "full understanding of the technique" was achieved in the mid-'90s. Over the subsequent 10 years researchers focused on the understanding of the process fundamentals in terms of process mechanics, tools and methods for process engineering and required hardware and software. The main findings of this fertile phase are summarized in the Keynote presented within the CIRP Conference in 2005 [37]. Looking at the results reported in that keynote it is possible to state that most of the significant scientific findings concerning SPIF were already obtained through numerical modelling.

To be more specific: 1/deep understanding of process mechanics including thinning distribution, formability, impact of process and material parameters on the

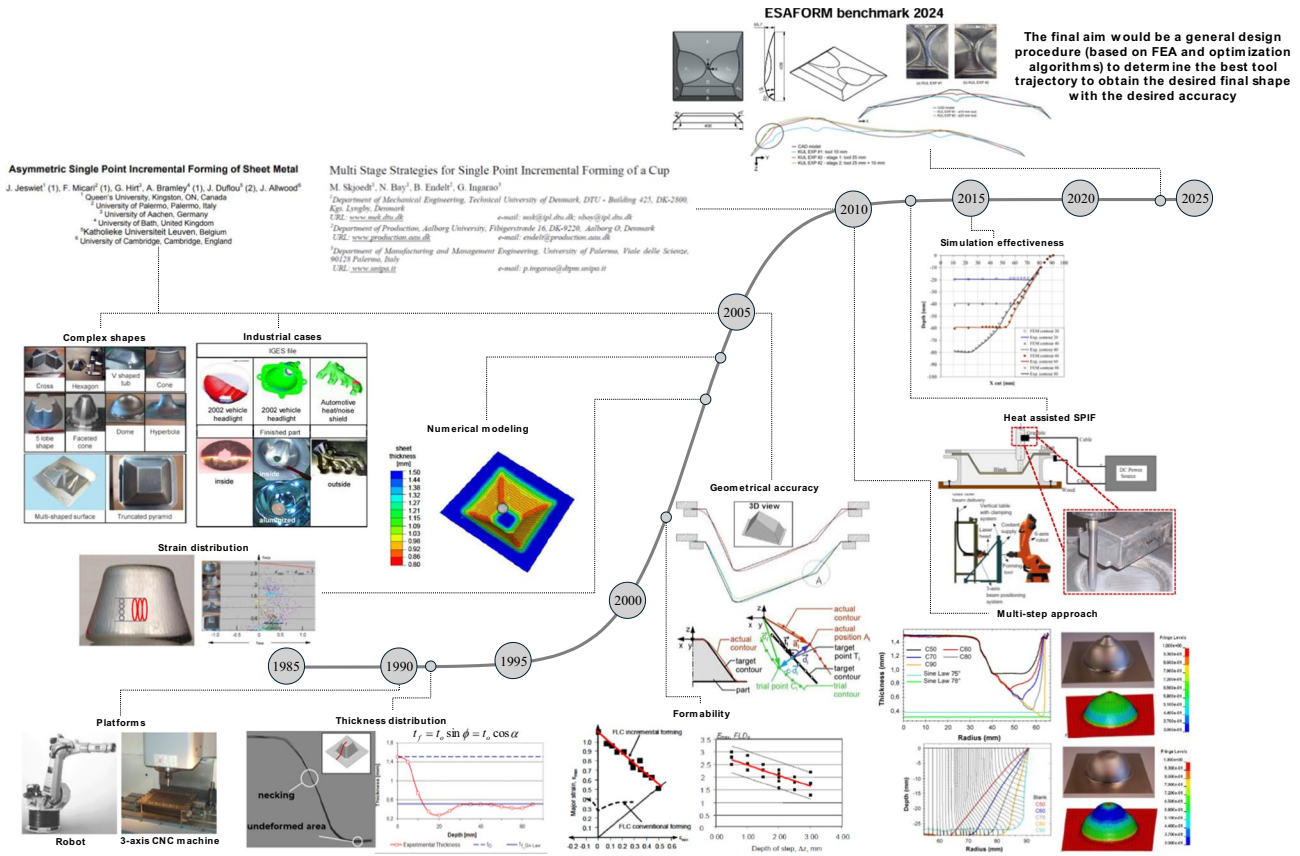


Fig. 5 S-curve of the sheet metal forming

formability; 2/analysis of the required equipment including a list of machines available to perform incremental forming; 3/comparison of implicit and explicit numerical models to analyze the process; 4/list of applications providing the range of geometrical complexity obtainable by SPIF. Finally, process limitations were also analyzed, such as very slow cycle time, poor geometrical accuracy and excessive thinning.

After that milestone, researchers have been steadily developing research on numerical modelling of SPIF. For the subsequent 10 years the degree of innovation and progress knowledge, although still present, was lower than the early stage.

Examples of these researches concern: 1/the implementation of multi-step approaches aimed to formability improvement (maximum achievable forming angle) [38, 39]; 2/strategies for improving geometrical accuracy [40, 41]; 3/heat assisted SPIF for formability improving [42] or aimed to form difficult-to-form materials in cold conditions [43, 44]; 4/tuning of the numerical modelling by testing different commercial codes and numerical parameters: constitutive materials model, integration scheme and element type [45–48].

The research efforts developed on SPIF over the timespan 2005–2015, were reviewed and reorganized in two review papers [49, 50].

Over the last 10 years, although researchers have continued to publish papers on numerical modelling of SPIF, it is clear this technique has reached its natural limit. The goal would be the development of a general and effective process design tool, able to provide process parameters (mostly the tool trajectory) to form the desired final part with the requested accuracy, maximum thinning and so on. Despite a strong research effort by researchers all over the world, this goal is very far from reaching, i.e. numerical modelling has reached its natural limit.

Very clear evidence of this statement is provided by the ESAFORM benchmark 2024 "Study on the geometric accuracy of a complex shape with Single Point Incremental Forming". In this benchmark, 13 research institutes were involved and the challenge was to implement the best tool path strategy to optimize the geometrical accuracy of a selected shape. It was basically an experimental research effort, where the acquired knowledge of the involved research groups drove the selection of the proposed tool paths. Both single and multi-stage strategies were proposed.

Despite a tremendous research effort (like the ESAFORM international Benchmark is), a small performance improvement was achieved proving that numerical modelling, evenly integrated with optimization/control techniques, still fails in providing an effective design tool.

Research trends analysis through text mining

To provide evidence about our intuition, i.e. numerical modelling has reached its natural limit to model and design metal forming processes, a wide analysis of scientific literature was carried out.

A dedicated workflow has been developed as reported in Fig. 6. Specifically, this procedure has been applied to all the papers presented at ESAFORM conferences held over the last 17 years.

"*The European Scientific Association for material FORMing*", ESAFORM, is a non-profit scientific association. It was founded in January 1997 with the aim to propagate interest for all types of materials and all topics connected to Material Forming [51]. It is worth remarking that, among the scientific conferences on the topic, ESAFORM was selected due to the time continuity and the number of papers. Actually, the mechanism of mini-symposia allows to

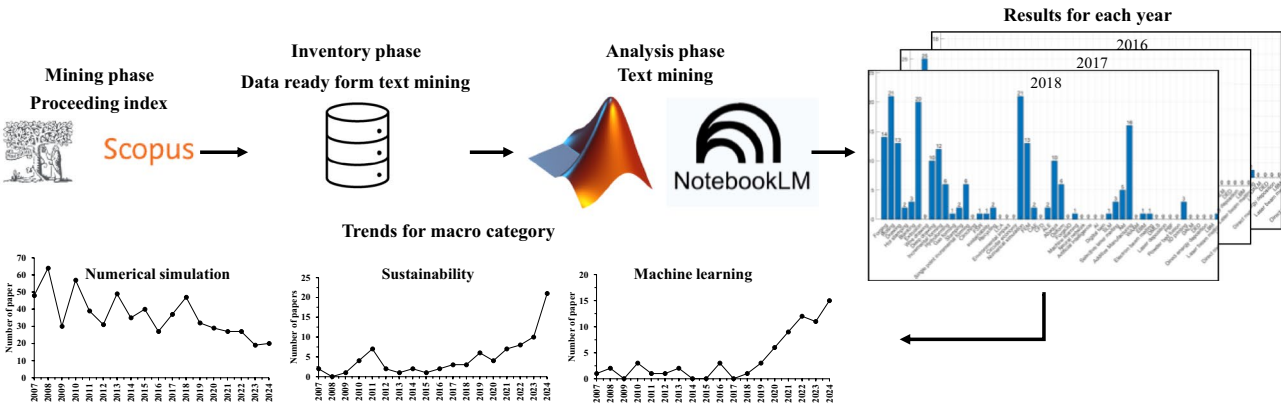


Fig. 6 Workflow for topic trend analysis through text mining

cover a wide range of topics and methodologies providing a reliable platform for the purpose of the present research.

The initial idea was to identify research trends in terms of topics, research approaches, analyzed processes, etc. over the last 20 years, but since the availability of papers in digital version before 2007 was limited, the threshold has been moved to the last 17 years. The set-up workflow is structured into five main phases. Firstly, it was needed to collect the ESAFORM Conference Proceedings available on-line in scientific databases. Successively, abstract, title and keywords of the papers were extracted from the collected papers (more than 4700). In the third phase two different text mining approaches were implemented to extract and classify the knowledge out of the collected papers: one approach is based on the use of the Notebook LM platform; an AI-powered tool designed to identify topics within scientific papers and enabling real-time interaction with uploaded documents. The other tool relies on Matlab coding, where predefined keywords were selected and used for filtering the collected papers. The main idea was to quantify the number of papers dealing with a given topic, using a list of keywords. Both the text mining methods searched for the selected keywords, considering three identified features: title, abstract and keywords of the paper.

The fourth phase focuses on collecting and organizing the paper by topics and by year. Lastly, in the fifth phase the overall trend overtime was depicted, and the conclusions were drawn. Details concerning the mining, inventory and analysis phases are given in Sect. 4.1 and 4.2.

Mining and inventory phase

At the beginning of the mining phase, the official ESAFORM conference website was consulted to get the list of all editions over the last decade. Both the year and the number of papers were acquired and collected in Table 1. Once the editions were listed, the Scopus web site was investigated for gathering all the abstract, titles and keywords. With these simple steps the dataset was created and ordered for the next phase.

Table 1 List of the conference editions ordered by year

Year	N° of papers	Year	N° of papers
2007	252	*2016*	236
2008	360	*2017*	292
2009	226	*2018*	275
2010	310	*2019*	250
2011	295	*2020*	247
2012	228	*2021*	225
2013	282	*2022*	254
2014	220	*2023*	226
2015	245	*2024*	313

Analysis phase

In this chapter, an overview of the coding and artificial intelligence approach is presented. These two methods will be discussed highlighting the main pros and cons.

Notebook LM approach

Artificial intelligence (A.I.) was implemented by means of Notebook LM online software. This software can read and elaborate the pdf file fed to it. In this work, the use of Notebook LM was mainly focused on extracting the number of papers which were related to the selected keywords listed in Table 2. This procedure (A.I.) is characterized by a fast elaboration of the data, since it can work with large amounts of data at once, but it is limited to the type of files it can read and the precision of reading. Despite the powerful and fast elaboration, it resulted that the software had multiple issues on reading the file provided, therefore coupling with the Matlab approach was needed.

MATLAB approach

A MATLAB script was created to extract and quantify the frequency of predefined keywords within a dataset of conference proceedings. The input consists of a spreadsheet file for each year, containing features for each publication, including paper titles, abstracts, author-defined keywords, and index keywords. A predefined list of keywords, selected according to the research scope, is used as the reference for the analysis.

Each keyword is searched within the metadata fields using case-insensitive matching. The script generates a matrix that records the presence or absence of each keyword for every publication. All keyword matches are detected and recorded in an output file automatically generated by the script.

It is worth noting that this coding-based approach, while computationally slower, provides higher precision, as it identifies only those papers containing the exact keywords specified.

Table 2 List of keywords used on the database for counting the papers

Topic	Keywords
Bulk forming	*Forging*, *Rolling*, *Drawing*, *Extrusion*, *Wire drawing*
Sheet forming	*S.P.I.F.*, *Incremental forming*, *Blanking*, *Hydroforming*, *Gas forming*, *Stamping*, *Hot stamping*, *Deep drawing.*
Numerical simulation	*Numerical Simulation*, *FEM*, *CAE*, *CFD*, *ALE*, *commercial code*
Machine learning	*Machine learning*, *Neural network*, *Artificial Intelligence*, *AI*, *Digital twin*
Sustainability	*LCA*, *Environmental impact*, *Circular economy*, *Sustainability*, *Recycling*

Discussion of the results

From the dataset obtained through the study of ESAFORM conference proceedings, over the last 17 years, it was possible to obtain an overview of the global trends in multiple research fields. The first analysis was developed to verify if some trends were visible concerning conventional forming processes historically presented at ESAFORM: bulk and sheet metal forming processes. The set of used keywords for these two forming approaches are listed in Table 2 and the results are reported in Figs. 7 and 8.

As far as bulk forming is concerned, although some frequency values fluctuations are observed, no clear trends are visible. As regards sheet forming, the only visible decreasing trend concerns hydroforming. It seems that within the ESAFORM community the interest in conventional forming processes has not changed over the last 17 years.

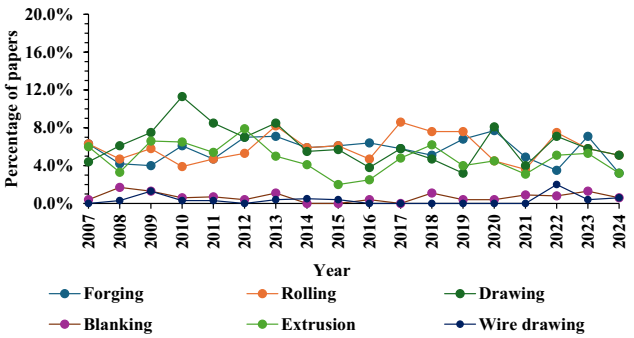


Fig. 7 ESAFORM papers on bulk forming

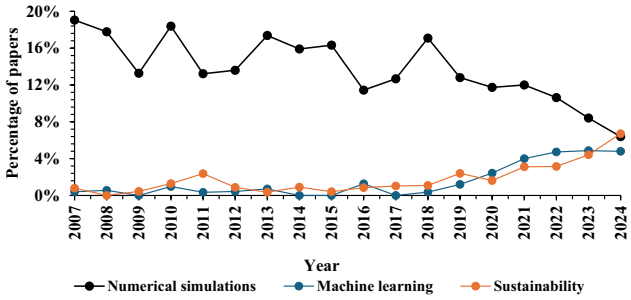


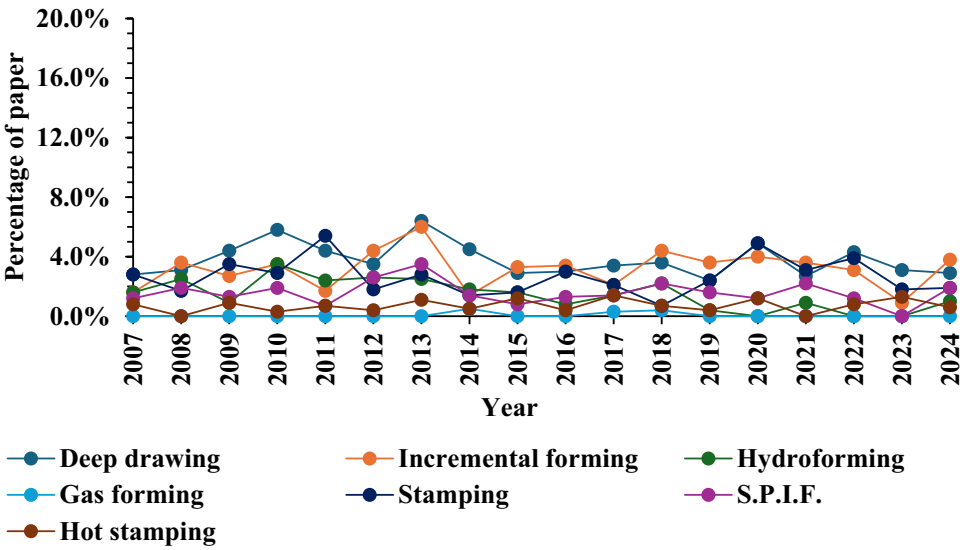
Fig. 9 Numerical simulation, machine learning and sustainability trends

Further analysis has been carried out on three more topics, namely numerical simulations, sustainability and machine learning. The trend of these research fields is depicted in Fig. 9.

A decreasing trend in the number of papers is explicitly visible for the numerical simulation topic. Over the years, FEA has had several evolutions and improvements, as discussed in Sect. 3, but over the last 10 years, the numerical modelling approach has gradually lost relevance and has increasingly become a secondary feature in research papers. While numerical modelling remains an important tool, it is no longer considered the central focus or primary subject of most studies. In fact, researchers do not include numerical modelling in the title or in the keywords.

An opposite trend is, instead, observed for sustainability and machine learning topics. The results showed that in both cases, after 2017, the use of machine learning and sustainability techniques has drawn more attention. This is easily understandable considering the actual increasing demand for more sustainable solutions to overcome the main worldwide issues (scraps production, CO_2 emissions, global warming, etc.). Furthermore, the Machine Learning approach shows an increasing trend: researchers moved the

Fig. 8 ESAFORM papers on sheet forming



focus more on predicting (through neural networks training) than on exploring the phenomena.

What is particularly suggestive is that the decreasing trend of numerical simulations and the rising trends of sustainability reached an intersection point. This highlights the fact that nowadays sustainability is catching more interest, as well as machine learning, while numerical simulation is considered simply as a tool.

Conclusions

According to the above considerations, a few conclusions could be drawn:

- The application of Innovation Theory to Numerical Simulation as Modelling Technique of Metal Forming Processes yields to the conclusion that the "natural limit" of such technique is being approached, in particular as far as process design and optimization are concerned.
- Therefore, it is predictable the necessity for disruptive discontinuity, maybe after a period of competition among possible alternatives.
- At the moment, AI techniques and, more in particular, machine learning, seem the most suitable opportunities, although their application to metal forming processes is not so straightforward as in other cases.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest Conflict of Interest: The authors declare that they have no conflict of interest.

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