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# REVISITING PRODUCTIVE FAILURE THROUGH ITERATIVE PROTOTYPING: A SEMI-SYSTEMATIC LITERATURE REVIEW[1]

## REFLEKSJA NAD PODEJŚCIEM PRODUCTIVE FAILURE Z PERSPEKTYWY ITERACYJNEGO PROTOTYPOWANIA: SEMI-SYSTEMATYCZNY PRZEGLĄD LITERATURY

**Keywords:** productive failure, iterative prototyping, collaborative learning, literature review, artificial intelligence tools.
***Słowa kluczowe***: *produktywne niepowodzenie, iteracyjne prototypowanie, uczenie się poprzez współpracę, przegląd literatury, narzędzia sztucznej inteligencji.*

## Abstract
The study analyzed the effectiveness of the Productive Failure (PF) concept, its development stages, and practical limitations. A literature review supported by AI tools and the Chain-of-Thought approach confirmed PF's effectiveness in fostering deep understanding, especially in STEM fields. The author proposes an iterative prototyping process to support collaborative learning in PF-related educational contexts.

## Streszczenie
Celem badania była analiza skuteczności koncepcji Productive Failure (PF), jej etapów rozwoju oraz ograniczeń w praktyce. Przegląd literatury, wspierany narzędziami AI i podejściem Chain-of-Thought, potwierdził efektywność PF w rozwijaniu głębokiego rozumienia, zwłaszcza w naukach ścisłych. Autor proponuje iteracyjny proces prototypowania jako wsparcie zespołowego uczenia się w kontekstach PF.

## INTRODUCTION

The purpose of this study is to explore the developmental stages of the Productive Failure (PF) concept and to offer a reflective analysis of its application in the context of adult collaborative learning, centered on the prototyping process. The study aligns with the constructivist paradigm, treating knowledge as the result of an active and contextual interaction. This interaction occurs in dialogue between the

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knowing subject (the author-researcher), the analyzed material (selected scientific articles), and tools that support thinking (in this case, artificial intelligence tools).

In this study, an original semi-systematic literature review was conducted, supported by artificial intelligence (AI) tools. The Chain-of-Thought Prompting (CoT) method was employed – an approach that enhances the reasoning capabilities of large language models (LLMs) by decomposing complex problems into intermediate steps. As demonstrated in [Wei et al., 2023], CoT not only improves the performance of LLMs on tasks requiring intensive reasoning but also transforms the analytical process itself, making it more reflective, organized, and gradual.

The applied Chain-of-Thought (CoT) approach facilitated the organization of the analysis process, structured into: (1) gradual knowledge discovery; (2) continuous updating of conclusions throughout the analysis; and (3) a structured presentation of reflective observations and critiques.

The author-researcher formulated two research questions that guided both the literature analysis and the reflective examination of the development of the PF concept:

(RQ1) What educational outcomes of the Productive Failure approach have been documented in the literature, and how have its theoretical frameworks evolved over time?

(RQ2) What limitations in the implementation of Productive Failure have been identified in the literature, and how might they be addressed through an iterative, collaborative prototyping process within the context of collaborative learning?

The article sequentially presents the study's methodology and employed tools, findings categorized into three phases of the PF concept's evolution, followed by a discussion and conclusion.

## RESEARCH METHODOLOGY

### Preliminary Phase: Selection of scientific articles

Initially, a systematic search of the JSTOR and Scopus databases was conducted (chosen by the author). Articles available simultaneously in both databases underwent a dual qualitative screening – they had to meet the quality criteria of both databases, which enhanced the confidence in their reliability and scientific value.

Search queries included the phrase "Productive Failure" and the name "Manu Kapur" as author or co-author. Kapur is the originator of the Productive Failure (PF) concept. Articles that appeared in both databases and had full texts available (in at least one of the databases) qualified for further analysis. A total of ten scientific articles were selected.

Additionally, one meta-analytic study, encompassing 53 research papers comparing the broader approaches of Problem Solving First (PS-I) and Instruction First (I-PS), was included.

The selected texts (11 in total) were published in the following academic journals: Cognition and Instruction (1), Educational Technology & Society (1), Instructional Science (6), The Journal of the Learning Sciences (2), and Review of Educational Research (1).

### Exploratory Phase: Analysis of scientific articles using the CoT approach and AI tools

At this stage, Scholar GPT – a specialized instance of OpenAI's ChatGPT model, based on the Generative Pre-trained Transformer (GPT) architecture – was utilized. Scholar GPT was adapted to support research activities involving the analysis of scientific texts. It assisted the research process as a cognitive tool supporting reflection, synthesis, organization, and iterative reconstruction of meanings. It did not serve as an analytical agent replacing the researcher, but rather operated in dialogue with the researcher's instructions.

During the analysis, Scholar GPT collaborated with Sider.ai (developed independently by Sider, Inc.), a tool integrated with the model. The work was carried out under a free plan, which imposed a limit on the number of tokens.

The articles were analyzed individually, in chronological and logical order – corresponding to successive stages of the concept's development – allowing for the identification of evolving trends and semantic contexts within the PF concept. This approach enabled tracking its transformations not only over time but also within the researcher's own learning process.

After each analysis, the contribution of the article to the development of the PF concept was assessed in relation to previously reviewed publications. Iterative verification and deepening of the concept's understanding were crucial for ensuring the quality and reliability of the results.

This stage ultimately shaped the methodology of the entire study: the initially adopted working assumption – a semi-systematic literature review using AI tools – evolved into a two-phase study (in the main part), as indicated by the grey background of the modules in Figure 1.

The exploratory phase provided a "first glance" not only at the analyzed texts but also at the very construction and adequacy of the adopted methodology. It had a heuristic and creatively unstructured character. Its purpose was to evoke cognitive uncertainty, capture interpretative differences surrounding the analyzed concept, and identify its potential limitations. The researcher tested their own understanding of the PF concept, uncovered its evolving meanings, and simultaneously developed their own methodological framework. The CoT approach enabled a structured reflection process, while Scholar GPT served as cognitive support in dialogue with the text – acting as an intermediary between the content of scientific articles and the researcher's own knowledge.

## Systematizing Phase: Re-analysis of articles – CoT approach and AI tools

The re-analysis was conducted on the same set of scientific articles. However, in this case, the AI tools were, from the outset, informed about the officially established topic of the review and the title of the planned publication, as well as the keywords, research objectives, and adopted methodology – all determined during the exploratory phase. The assumptions of the study, whose methodology had emerged in the first phase, explicitly accompanied the text analysis from the very beginning.

Whereas in the exploratory phase AI tools functioned primarily as a catalyst for inquiry and a source of inspiration, in the systematization phase they consistently supported the researcher within the consciously adopted research methodology, enabling a sequential and logical conduct of the analysis in line with the research questions.

The systematization phase was reconstructive and integrative in nature. The findings from the exploratory phase gained greater methodological coherence and were firmly anchored in the adopted research assumptions. This phase served as a bridge between creative openness and analytical rigor, while also providing a space for consolidating the study's methodology.

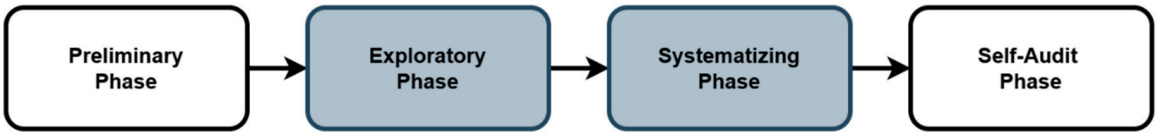
## Self-Audit Phase: Triangulation of AI tools

The fourth phase involved a critical comparison of the content of the emerging research report with the source texts, supported by an alternative AI tool – Perplexity (Perplexity AI, Inc.) – an online search engine and assistant based on artificial intelligence that utilizes large language models (LLMs). The work was conducted under a free plan, divided into stages corresponding to the developmental phases of the investigated concept – PF.

This triangulation activity was planned and undertaken to: (1) detect potential errors in the main phase research report, (2) identify gaps relative to the research questions, and (3) reveal overinterpretations or unwarranted assumptions reflecting the researcher's perspective.

The scheme of the conducted study – with division into the four phases described above – is presented in Figure 1. The two phases of the main part of the study are highlighted with a grey background color in the modules.

**Figure 1. Flowchart of the research – four phases.**




**Source:** Author's own elaboration.

In the context of the adopted methodology – based on a semi-systematic literature review utilizing AI tools and the CoT approach – it should be noted that the study's aim was not to obtain absolute certainty of knowledge (in line with the ideals of a positivist understanding of cognition), but rather to create reflectively grounded contextual knowledge, embedded within the constructivist paradigm.

Artificial intelligence tools, treated in this study as cognitive support, did not serve as a source of authoritative judgments. Instead, they participated in the process of iterative understanding, organization, and reconstruction of meanings – always in dialogue with the researcher, who was responsible for verifying, evaluating, and interpreting the generated content.

## RESEARCH RESULTS

### Development of the Productive Failure concept

The publications selected for analysis (10 articles) were divided into three groups corresponding to successive stages of the development of the PF concept – according to the author's interpretation of the concept's evolution:

- concept formation stage (2008–2012) – 5 articles introducing the basic assumptions and testing the model in educational practice;
- semantic field refinement stage (2012–2017) – 3 articles expanding the context with related concepts such as "Productive Success", "Vicarious Failure" and the relationship between PF and prerequisite knowledge;
- integration with other educational strategies stage (2017–2021) – 2 articles examining the connection between PF and the "Flipped Classroom" approach, as well as studies on "micro Productive Failure" in procedural teaching.

The articles were assigned by the author-researcher to individual stages both chronologically and according to the logic of the PF concept's development. This particularly applies to texts from the boundary years 2012 and 2017. Thanks to the applied approach, the division into stages not only reflects the historical sequence but also captures the dynamic development of the PF concept, which for the researcher is a knowledge construct co-created using AI tools based on the CoT methodology.

As a cognitive context, an additional eleventh article was selected, which itself is a meta-analysis of 53 studies on broader concepts than PF: Problem Solving First (PS-I) and Instruction First (I-PS).

## Concept formation stage (2008–2012)
## The foundation of the Productive Failure concept [Kapur, 2008]

Manu Kapur's 2008 publication constitutes the first work (within the selected corpus of texts) in the area of the PF concept. The aim of the study was to demonstrate that engaging students in solving complex, ill-structured problems – without providing support during the process – can lead to deeper learning despite apparent failure.

The experiment, conducted in schools using quantitative methods, showed that students in groups solving ill-structured problems achieved better results than those in groups solving well-structured problems, both in tasks requiring near transfer (similar tasks) and far transfer (tasks demanding knowledge transfer).

This article was also re-analyzed – lastly in the systematizing phase (after the meta-analysis) – which allowed for reconsidering its significance in light of more recent PF perspectives and for exploring the possibility of integrating PF with iterative design processes. Such a re-reading revealed the importance of Kapur's original work as a source not only for the theoretical construct but also for the framework of a transformative educational approach.

## Extension of research on Productive Failure [Kapur, 2010]

In the second analyzed text, Kapur transfers the hypothesis of Productive Failure to the reality of the classroom by implementing it in real-world mathematics teaching conditions.

The results confirm the existence of the "hidden effectiveness" of the PF approach: although students often did not succeed in solving the problems, they demonstrated better performance in post-tests, especially on application-level tasks.

While PF yields positive effects, its implementation requires very deliberate lesson design. There is also a need for a support structure for those who struggle with the openness of the situations. Social interactions (collaboration, dialogue, collective construction of meaning) were not addressed in the study discussed, although some student work took place in groups.

## Further exploration of Productive Failure in the school context [Kapur, 2011]

In the third article from the analyzed series, Kapur expands research on the PF approach by introducing a third experimental group – Facilitated Complex Problem Solving (FCPS) – which allows him to more deeply examine the effects of structure and delayed teacher assistance on learning effectiveness. Students in the PF group, despite not succeeding during problem-solving tasks, outperformed their peers in the Lecture and Practice (LP) and FCPS groups in terms of conceptual understanding, knowledge transfer, and representational diversity.

The statistical advantage of the PF group indicates that: (1) the absence of teacher assistance during the exploratory phase (characteristic of PF) leads to deeper cognitive processing; (2) FCPS-type support (teacher's help during problem struggle), while procedurally helpful, may suppress cognitive processes crucial for durable understanding and transfer.

## Designing for Productive Failure [Kapur, Bielaczyc, 2012]

The fourth article represents an important step in the development of the PF approach – it presents the principles of PF and their implementation in three schools with diverse student profiles.

The authors test the hypothesis that delaying cognitive support and creating space for exploring different Representations and Solution Methods (RSM) can promote deeper conceptual understanding through: (1) comparing correct and incorrect representations, (2) distinguishing subtle differences between concepts (e.g., instantaneous velocity vs. average velocity), and (3) discovering boundary conditions for the applicability of concepts.

Designing instruction according to PF principles requires a fundamental shift in the teacher's role: from a direct instructor to a facilitator of the cognitive process who: (1) creates cognitive space, (2) refrains from immediate instruction, (3) tolerates failure as a learning stage, (4) provides emotional and organizational support, and (5) facilitates subsequent knowledge consolidation.

## Productive Failure and learning of complex, abstract concept [Kapur, 2012]

In the fifth article in the series, Kapur extends the PF model to a new conceptual domain – statistics. The study examined whether the mechanisms of PF can be effectively applied to teaching difficult and abstract concepts such as variance.

The quasi-experimental study was conducted with ninth-grade students, comparing learning outcomes in two conditions: PF and Direct Instruction (DI). Students in the PF group solved problems without prior instruction, followed by a consolidation session. In the DI group, students first received instruction and definitions, then solved the problems.

The PF group achieved significantly higher results in conceptual understanding and transfer, despite not succeeding during the problem-solving phase (results were statistically significant). It was indicated that PF promotes deeper learning by activating and differentiating prior knowledge and generating multiple representations (RSM).

## Summary of the first stage of own research

The summary of this stage of research on the PF concept is Table 1, which contains answers to both research questions as well as reflections following the analysis of the five selected articles.
Each analyzed article provides strong – and progressively deepened – confirmation that PF supports deep understanding, activation of prior knowledge, and conceptual differentiation, even if students do not succeed during the initial problem-solving phase. The central mechanism is the delay of support and structure, which enables exploration of diverse representations and solution methods.

Although collaborative prototyping was not directly analyzed in these articles, two texts – [Kapur, 2011] and [Kapur & Bielaczyc, 2012] – outline the possibility of supporting PF by shifting the teacher's role to that of a facilitator, adapting the classroom environment, and designing instructional activities accordingly.

The potential role of social interactions and collaboration remains an important research direction, which was analyzed in the next two stages.

**Table 1. Answers to the RQ and reflections after the analysis of articles from the first stage of the study.**

| Scope of the RQ | Selected article | Answer to the RQ and reflections (in Bold) after article analysis |
|---|---|---|
| Educational outcomes and the evolution of the PF approach (RQ1) | [Kapur, 2008] | The basic educational effect of the PF approach – especially in terms of knowledge transfer and improved understanding – has been described.<br>The text does not yet provide a complex model of PF theoretical frameworks but introduces fundamental premises that later research will develop. |
| | [Kapur, 2010] | Specific educational outcomes were demonstrated (deeper understanding, better use of cognitive structures), and the theoretical foundations of the approach were developed:<br>the deliberate withholding of formal instruction or cognitive structure, and persistence in problem-solving despite failures. |
| | [Kapur, 2011] | Strong evidence was provided that the deliberate delay of cognitive structure and diversity of representations support deeper understanding of mathematical concepts, even without success at the problem-solving stage. |
| | [Kapur, Bielaczyc, 2012] | The results support the hypothesis that the mere generation and comparison of different representations and solution methods promotes the activation of prior knowledge and conceptual differentiation. |
| | [Kapur, 2012] | The effectiveness of PF as a strategy supporting deep learning has been confirmed. Crucially, PF did not negatively affect students' procedural achievements. |
| Limitations in the implementation of PF and the possibility of overcoming these limitations through an iterative, team-based prototyping process (RQ2) | [Kapur, 2008] | The text points out the limitations of the PF approach, resulting, among other things, from the need to consider differences between students within a group.<br>**Further research on various forms of structuring the problem-solving process would be valuable.** |
| | [Kapur, 2010] | Although the experiment's results demonstrate the superiority of PF over traditional teaching in terms of the cognitive quality of solutions, Kapur notes difficulties in unequivocally attributing success to specific elements of the instructional design. He also points out that not every student benefits from independently grappling with the problem – which raises the question of the need for structures that support this process.<br>**Team-based prototyping could serve as a tool that organizes exploration, enhances reflection, and enables the distribution of cognitive responsibility among team members.** |
| | [Kapur, 2011] | Kapur notes differences within PF groups and points to the need for further research on the role of individual characteristics (motivation, frustration tolerance) as well as the social context.<br>**Implications arise for creating supportive, iterative learning environments, for example, those based on team prototyping.** |
| | [Kapur, Bielaczyc, 2012] | Assigning the teacher's role solely to emotional and organizational support, while simultaneously lacking cognitive assistance, is often difficult to accept in everyday school practice.<br>**This signals the need to support PF, for example through iterative design structures and team reflection in the instructional process.** |
| | [Kapur, 2012] | Kapur does not engage in critical reflection on the implementation barriers of PF itself, nor does he analyze potential support mechanisms.<br>However, designing tasks with a focus on multiple representations and exploratory thinking can serve as an inspiration for further work on learning environments based on constructive collaboration. |

**Source:** Own elaboration based on the results of article analysis according to the adopted research methodology.

## Semantic field refinement stage (2012–2017)
## Productive Failure in learning through generating and inventing solutions [Kapur, Rummel, 2012]

The sixth article is a relatively short text opening a special issue of the journal Instructional Science, dedicated to learning through generating and inventing activities. The authors propose an extension and refinement of the Productive Failure (PF) concept, presenting it in opposition to Productive Success (PS), where students immediately succeed in problem-solving. The article is a review-conceptual piece and presents four empirical studies from different countries (Singapore, Germany, Canada, USA) examining the effects of PF in various educational settings.

A common feature of these studies is the two-phase PF model: the phase of generating representations and solutions (RSM), followed by the phase of knowledge consolidation. The article places special emphasis on three factors supporting the generation process: (1) team role scripts (Think–Ask–Understand, TAU), (2) metacognitive scaffolding, and (3) team composition (deliberate selection of team members).

The TAU scripts assign participants specific roles and stages of activity. Participants go through three stages: first, they individually analyze the problem (Think), then they ask questions and explain their ideas within the group (Ask), and finally, they jointly reach understanding and summarize the solutions developed (Understand). Metacognitive scaffolding can take the form of guiding questions, encouragement to reflect on one's own strategies, prompts related to planning actions, or evaluation of progress. Team composition refers to the selection of group members based on their prior skills and knowledge levels. Research findings suggest that the most effective teams are those diverse in terms of abilities.

## Learning from others' failures: Productive Failure (PF) vs. Vicarious Failure (VF) [Kapur, 2014]

In the next article, Kapur compares two forms of learning: PF and VF. The aim of the study was to understand how students learn when they experience failure personally (PF) versus learning from others' failures (VF). The study was quasi-experimental and involved students from different schools who were assigned to two groups: the PF group solved tasks without support, while the VF group analyzed incorrect solutions generated by other students during PF. Both groups then received the same instruction.

The article confirms that PF is effective in developing deep conceptual understanding and knowledge transfer, even though students initially do not succeed in problem-solving. Kapur highlights the positive impact of generating one's own representations (RSM), which contributes to increased cognitive flexibility. The findings support the development of PF theory by introducing VF as an alternative learning method, albeit with lower effectiveness. The comparison of PF and VF shows that personally experiencing failure during the problem-solving process is more effective than analyzing others' errors (VF), even though both approaches lead to similar procedural proficiency.

A problem was identified regarding the lack of support during group work in the PF phase of generating representations. This lack of support can be frustrating for students, especially if they do not have sufficient prior knowledge. The VF approach, on the other hand, may be less effective because students had a lower sense of "ownership" of the solutions and less motivation to learn the canonical solution, which resulted in shallower conceptual understanding and knowledge transfer.

## Prior knowledge and learning in the Productive Failure approach [Li Leslie Toh, Kapur, 2017]

The study described in the eighth article marks a significant turning point in the development of the PF approach. It focused on the issue of students having sufficient prior knowledge needed to generate representations and solutions (RSM) during the exploratory phase.

The authors conducted two quasi-experiments in the context of teaching a complex biological concept. They compared students provided with micro-level concept knowledge (High Micro-level Concept knowledge, HMiC) with students without such preparation (Low Micro-level Concept knowledge, LMiC). Micro-level knowledge concerned complex, abstract biological mechanisms.

The study results showed that although students in the HMiC group generated more and more diverse representations, they did not achieve better results in the final tests (after the consolidation phase). They reported higher cognitive load and lower engagement during the lessons.

This finding makes an important contribution to the debate on the effectiveness of PF – suggesting that greater prior knowledge does not always translate into better learning, especially when cognitive load exceeds the student's capacity.

## Summary of the second stage of own research

The summary of this stage of research on the concept of PF is presented in Table 2, which contains answers to both research questions as well as reflections after analyzing the next three selected articles.

**Table 2. Answers to the RQ and reflections after the analysis of articles from the second stage of the study.**

| Scope of the RQ | Selected article | Answer to the RQ and reflections (in Bold) after article analysis |
|---|---|---|
| Educational outcomes and the evolution of the PF approach (RQ1) | [Kapur, Rummel, 2012] | The value of independent attempts before instruction has been confirmed as effective for conceptual learning. Generating solutions and analyzing them (even if incorrect) is an effective cognitive mechanism. |
| | [Kapur, 2014] | The study provides strong evidence for the effectiveness of PF: students who experienced difficulties and failures on their own achieved better results in tests of conceptual understanding and knowledge transfer than those who analyzed others' solutions. This established the importance of personal experience in the learning process. |
| | [Li Leslie Toh, Kapur, 2017] | Limitations arising from the characteristics of students' prior knowledge and the impact of cognitive load on the learning process were also revealed. An excessively high level of prior knowledge may weaken the PF effect, as students might not engage sufficiently in cognitive effort. |

| | | |
|---|---|---|
| Limitations in the implementation of PF and the possibility of overcoming these limitations through an iterative, team-based prototyping process (RQ2) | [Kapur, Rummel, 2012] | Three mechanisms supporting the generation phase have been identified: a team collaboration script (TAU), metacognitive support, and the deliberate selection of team members based on their competencies.<br>**All of these mechanisms can be integrated into the proposed iterative prototyping process as a framework for team learning.** |
| | [Kapur, 2014] | Limitations of PF have been identified: lack of support can lead to student frustration, especially when dealing with difficult concepts or insufficient prior knowledge. Analyzing others' failures within VF proved less effective because students had a lower sense of "ownership" of the solutions and reduced motivation to understand the canonical solution.<br>**The need to work through one's own failures can be a direct inspiration for proposing a prototyping process, during which students or adults (working in teams) create their own (imperfect) physical prototypes, learning shared responsibility for the emerging product.** |
| | [Li Leslie Toh, Kapur, 2017] | The findings highlight the importance of designing iterative, supportive interventions that consider both students' levels of prior knowledge and their ability to apply it effectively during problem solving.<br>**A team work model centered around a physical prototype may enable the transfer of cognitive activity into a concrete action process. This can reduce cognitive load and increase student engagement.** |

**Source:** Own elaboration based on the results of article analysis according to the adopted research methodology.

This stage focused on refining the semantic field of the PF concept. PF is not universally effective – its outcomes depend on task design, the student's level of knowledge, and support during the generation phase. Not every failure is productive – the cognitive environment, collaboration structure, and timing of intervention (sometimes deliberately delayed) are crucial. Significant implementation barriers of PF were also identified: (1) lack of engaging context (VF), (2) cognitive overload (with excessive prior knowledge), and (3) lack of collaboration structure.

The evolution of PF theoretical frameworks is moving toward considering the context of failures: how and in what cognitive and social environment work based on PF takes place. It is already noticeable that the titular iterative team-based prototyping process could support the PF structure.

## Integration with other educational strategies stage (2017–2021) Productive Failure and the traditional Flipped Classroom strategy [Song, Kapur, 2017]

In the ninth article, the authors compare two approaches to the Flipped Classroom strategy: the traditional Flipped Classroom (TFC) and the one based on the principles of Productive Failure (PF-FC). The main difference between them lies in when students engage in problem-solving – either before instruction (PF) or after familiarizing themselves with the material (TFC).

The experiment conducted among high school students showed that the group working with the PF-FC model achieved better results in understanding and transfer, even though their declarative knowledge (memorized facts) did not differ significantly from the TFC group. These results confirm that struggling with a new problem before the instruction phase – even if it leads to failure – activates deeper processing, reflection, and better preparation for subsequent instruction.

This provides confirmation of the effectiveness of the PF approach as a learning framework which – although cognitively demanding – is productive, even when embedded within the flipped classroom strategy. Interestingly, it can be observed that the PF-FC groups essentially reverse the traditional flipped classroom model: first, problem-solving activity takes place in class, followed by instruction/consolidation at home. One might call this a "flipped flipped classroom": first exploration and solution generation by students, and only later video instruction as a tool for knowledge consolidation.

## Productive Failure in a micro version [Ziegler et al., 2021]

This article develops the concept of PF by focusing on its application not in conceptual learning, but in procedural learning. The authors propose introducing PF in a micro version (micro PF) – situations in which students have multiple "micro opportunities to learn from failure", analyze their mistakes, and correct them in short cycles of activity. This process is iterative and cognitively engaging.

The study was conducted in the context of learning algebraic procedures. The aim was to examine whether procedural failures (micro PF) can, similarly to classical PF, promote deeper understanding and differentiation of procedures. The micro PF concept differs from classical PF in the shorter duration of individual problems, multiple cycles, and the focus on a single solution rather than generating multiple solutions.

Learning through micro PF leads to better differentiation of similar procedures, more effective transfer within procedures, and greater flexibility in applying algorithms. Although students in the micro PF group performed worse during practice, after instruction their results were significantly better than those of the control group. Educational success does not require immediate correctness – the key is the process of cognitive struggle.

## Summary of the third stage of own research

The summary of this stage of research on the concept of PF is presented in Table 3, which contains answers to both research questions as well as reflections following the analysis of two additional selected articles.

In the third stage of the research, a significant extension of the theoretical and applied frameworks of the PF approach was noted. The PF approach integrated with the Flipped Classroom model (PF-FC) maintains and even enhances its educational effects – particularly in terms of conceptual understanding and knowledge transfer.

The expansion of the original PF concept with a new variant – micro PF – transfers the assumptions of PF from conceptual learning to procedural learning, confirming its effectiveness in this area as well.

The educational effects of PF – including deeper processing, activation of prior knowledge, cognitive flexibility, and better transfer (for micro PF: transfer within procedures) – are confirmed in new didactic contexts, indicating the growing maturity of the PF approach.

Effective implementation of PF – both in the PF-FC model and micro PF – requires appropriately designed educational environments and teacher support.

**Table 3. Answers to the RQ and reflections after the analysis of articles from the third stage of the study.**

| Scope of the RQ | Selected article | Answer to the RQ and reflections (in Bold) after article analysis |
|---|---|---|
| Educational outcomes and the evolution of the PF approach (RQ1) | [Song, Kapur, 2017] | The traditional flipped classroom (TFC) strategy – although engaging students – often boils down to passive content consumption. Supporting TFC with the PF approach creates an educational framework with a structure that cognitively activates learners. PF promotes deeper processing – not just memorization. |
| | [Ziegler et al., 2021] | The effects of PF can also be successfully transferred to procedural learning (micro PF), significantly expanding the theoretical framework of the concept. A new application area for PF is teaching mathematical procedures using cycles of mistake and reflection. |

| | | |
|---|---|---|
| Limitations in the implementation of PF and the possibility of overcoming these limitations through an iterative, team-based prototyping process (RQ2) | [Song, Kapur, 2017] | Effective implementation of the flipped classroom strategy supported by the PF approach (PF-FC) requires appropriate design of the educational environment: both at the level of lesson structure and materials.<br>This demands more planning than TFC. Tools to support teachers are needed.<br>**The article does not contain explicit references to the prototyping process. However, it can be observed that the teacher – in the second phase of PF-FC – refers to team solutions previously created by students. This interaction has certain characteristics of prototyping (didactic or cognitive): students design solutions and are then guided through reflection and modification.** |
| | [Ziegler et al., 2021] | Task design in a cyclical form supports the process of iteration and strategy development. The micro PF structure reflects the principles of iterative educational design.<br>**The structure of micro PF tasks can be seen as a cognitive counterpart to iterative prototyping, in which students go through cycles of trials, failures, and reflection. This provides strong support for the idea of introducing team prototyping as an implementation framework for PF.** |

**Source:** Own elaboration based on the results of article analysis according to the adopted research methodology.

An improperly designed struggle phase in PF-FC, where students are confronted with a problem without prior instruction, can lead to frustration or lack of engagement. To prevent this, it is advisable to use structures that support student activity, such as exploratory, collaborative phases with tasks of controlled difficulty levels.

Repeated exposure to failures/mistakes and attempts to correct them (in the micro PF approach) can serve as iterative cognitive prototyping. This makes it possible to create cyclical learning environments where failures are not only tolerated but intentionally designed as sources of knowledge.

At the conclusion of the research on the development of the PF concept, one of the most important synthetic studies – a meta-analysis of 53 empirical papers on PF – was analyzed.

## Meta-analysis of the effectiveness of Productive Failure

The last selected article [Sinha, Kapur, 2021] analyzes the educational effects of two strategies: problem solving before instruction (PS-I)[2] and instruction before problem solving (IPS)[3] The aim of the study was to determine whether and when PS-I is more effective than IPS, and under what conditions the educational effects of this model can be maximized. This study systematically examines cognitive effects, transfer, types of knowledge (declarative, procedural, conceptual), and student characteristics (age, prior knowledge level).

The results indicate that PS-I, especially in the PF variant, yields moderately higher effects in conceptual understanding and knowledge transfer (Hedges' g = 0.36–0.58)[4], particularly among older students and with complex content. Effects on procedural and factual knowledge are weaker or nonexistent.

The educational effects of PF are statistically significant and stable but context-dependent. This means that PF should be applied intentionally, targeting appropriate content and student groups. For younger students and for domain-general skills, instruction before problem solving (I-PS) yields better results.

The study highlights the need for deliberate design of PF environments, which must include: a task structure leading to impasse, support mechanisms, and space for reflection. This suggests a practical

[2] Strategy exemplified by the classic Productive Failure (PF) approach.

[3] Traditional teaching approach.

[4] Hedges' g is a statistical measure of effect size used to compare the effectiveness of different interventions or teaching methods based on the results of multiple studies. It includes a correction for small sample sizes, making it more accurate in meta-analyses.

implication – the use of iterative instructional prototyping as a tool that can help teachers implement PF effectively.

The results of the meta-analysis may be somewhat inflated due to publication bias, given the tendency for studies reporting positive effects to be more likely published. Due to the great diversity of fields and populations studied, the results may not always be directly transferable to every educational context. In practice, this means caution is needed when interpreting general effects. Further research is necessary across various disciplines and student groups.

## DISCUSSION

### Productive Failure and collaborative prototyping

Kapur and colleagues suggest the possibility of introducing structures that support exploration and reflection, such as collaborative work environments. They also point to the need to redefine the role of the teacher and the learning environment (e.g., the classroom) – which lays the groundwork for prototyping as an organizing strategy.

The results of the conducted study (three stages) indicate the need to implement structures that support the exploration of failures and cognitive mistakes and stimulate reflection and reconfiguration of learning strategies – mechanisms present in a design process based on the cycle of iterative prototyping. A prototyping-based model can serve both as a didactic framework and as a mechanism for cognitive and social support, assisting learners in various educational contexts.

Based on the conducted analysis, the author of this study argues that iterative collaborative prototyping can: (1) facilitate difficulty level control and distribute responsibility; (2) activate learners' cognitive engagement (including adult learners) by providing tangible materials during the prototyping process; (3) serve as an organizational framework for designing educational environments that support the PF approach. However, effective implementation of PF elements will require additional planning, structures, and tools for teachers or trainers working with adults.

### Role of the researcher in relation to the use of AI tools

The researcher's original contribution can be described as strategic, reflective, and creative guidance of the scientific knowledge acquisition process, in which AI tools (LLMs) serve as supportive instruments rather than replacements for epistemic activity. This contribution is scientific because the researcher: (1) holds conscious epistemological assumptions: does not accept knowledge as self-evident but critically reconstructs it; (2) makes creative methodological decisions: constructs their research model (the method of selecting scientific articles, dividing the development of the PF concept into stages, assigning articles to stages, using the CoT approach, choosing AI tools); (3) conducts reflective data interpretation: each article analysis is not a summary but a research and reconstructive process.

Although the artificial intelligence (AI) tools used in this study played a significant supportive role in the analysis process, the key cognitive, conceptual, and methodological decisions clearly belonged to the researcher. The review was a researcher-driven reflective study, whose structure and interpretations were not imposed by an algorithm but were designed and shaped by the researcher conducting the analysis of the selected texts.

The applied CoT model served as an epistemic framework that enabled thoughtful and stepwise analysis of each source. Within this framework: (1) the researcher sequentially uncovered the meanings contained in the publications, (2) iteratively updated conclusions in light of new data, and (3) reflectively organized them with respect to the adopted research questions.

In a sense, the researcher assumed the role of an "active mediator" between the raw textual material selected for analysis (scientific articles) and the method of its systematic, reflective processing. The large language model (LLM) was conceptualized as an intelligent cognitive partner, supporting access to texts, the organization of information, and the synthesis of data. However, the model did not make any research decisions. Final interpretations, quality assessments, epistemological choices, and conceptual decisions belonged solely to the researcher.

## Protection of the researcher against errors made by AI tools in the analysis of scientific texts

Large language models (LLMs), such as Scholar GPT or Perplexity, offer advanced analytical support capabilities in research work; however, their use in the analysis of scientific texts is associated with certain risks [Bender et al., 2021; Weidinger et al., 2021].

Based on personal experience (during the exploratory and systematizing phases), the author-researcher identified five typical risks that may arise when using such tools. The first four are epistemic risks (related to how we acquire, interpret, and justify information/knowledge while working with and supported by AI), and the fifth is an ontological risk (related to the nature of information/knowledge generated with AI support). These risks are as follows: (1) fact hallucinations (the model may generate non-existent data, including fictitious citations or bibliographic references); (2) analysis without access to full texts (the model bases its conclusions solely on abstracts, reviews, or metadata); (3) generalization without context (presented conclusions are too general, lacking reference to the specifics of the given source); (4) blending the voices of the author and the model/interpreter (the model does not separate its own narrative from the author's statements in the analyzed text); (5) blurring boundaries between concepts (confusing concepts or creating new ones without references to the literature). Below, the safeguards applied by the author-researcher in working with LLMs will be presented.

In the preliminary phase, preceding the main study, the articles were selected for analysis by the author from the JSTOR and Scopus databases. The author proposed the structure of the review, which reflects three stages in the development of the PF concept. Finally, the author assigned the articles chronologically and logically to the respective stages of the concept's development.

During the exploratory and systematizing phases of the study, a step-by-step analysis (Chain-of-Thought) was enforced, which minimized jumping between texts and excessive generalizations: first, the context was examined, then the results, and finally the interpretation. Each article was analyzed in full text, not only based on the abstract or reviews. Additionally, each article was analyzed separately, which protected the process from merging input data and overgeneralizing the results.

Each analysis of an individual text included the context of the author's research questions, identification of the components of the analyzed text to be examined (introduction, research objectives, methodology, results, discussion, limitations, future research plans), and a summary. Knowledge was generated not "within the AI tool" but through the researcher's interpretative activity, which was structurally supported by AI.

In the self-audit phase, serving as a cognitive-methodological audit, AI tool triangulation was conducted. The aim was not so much to obtain a "second opinion" from an external reader or expert, but rather to test the consistency and completeness of the obtained interpretations.

The use of an alternative AI tool (Perplexity) aimed to: (1) identify possible errors, (2) find gaps relative to the research questions, and (3) indicate overinterpretations or excessive influence of the researcher's own perspective.

This structure of the conducted study – with its division into four phases (preliminary, exploratory, systematizing, and self-audit) – reflects the methodological responsibility of the author-researcher.

## CONCLUSIONS

The reflection conducted on the development of the PF concept (divided into three stages) aimed to reveal the common points between PF and the adult learning framework being developed by the author of this study, based on the process of iterative, collaborative prototyping.

The authors of the analyzed articles – consciously or not – point to solutions that can be classified as elements of collaborative prototyping: (1) cyclical and iterative structure (micro PF), (2) educational environment design (PF-FC), (3) tasks supporting diverse cognitive exploration (classic PF), (4) physical (or cognitive) artifacts of group work as objects of reflection.

The Chain of Thought (CoT) approach, which supports iterative reflection and reconstruction of meanings, corresponds to the constructivist idea of negotiation and co-creation of meanings in the research process. The use of artificial intelligence (AI) tools – as cognitive support in dialogue with scientific texts (rather than as a source of authoritative judgments) – reflects a constructivist (and arguably posthumanist) approach to co-creating knowledge in the relationship between the researcher and the applied scientific knowledge tool.

Such a methodological grounding is consistent with the nature of research conducted on complex, evolving educational strategies/concepts such as "Productive Failure."

## BIBLIOGRAPHY

Bender E.M., Gebru T., McMillan-Major A., Shmitchell S., 2021: *On the dangers of stochastic parrots: Can language models be too big?* Proceedings of the 2021 ACM Conference on Fairness, Accountability, and Transparency (FAccT '21), 610–623. https://doi.org/10.1145/3442188.3445922

Kapur M., 2008: *Productive Failure*. Cognition and Instruction, 26(3), 379–425.

Kapur M., 2010: *Productive failure in mathematical problem solving*. Instructional Science, 38(6), 523–550.

Kapur M., 2011: *A further study of productive failure in mathematical problem solving: Unpacking the design components*. Instructional Science, 39(4), 561–579.

Kapur M., 2012: *Productive failure in learning the concept of variance*. Instructional Science, 40(4), 651–672.

Kapur M., 2014: *Comparing Learning From Productive Failure and Vicarious Failure*. The Journal of the Learning Sciences, 23(4), 651–677.

Kapur M., 2008: *Productive Failure*. Cognition and Instruction, 26(3), 379–425.

Kapur M., 2010: *Productive failure in mathematical problem solving*. Instructional Science, 38(6), 523–550.

Kapur M., Rummel N., 2012: *Productive failure in learning from generation and invention activities*. Instructional Science, 40(4), 645–650.

Li Leslie Toh P., Kapur M., 2017: *Is having more prerequisite knowledge better for learning from productive failure?* Instructional Science, 45(3), 377–394.

Sinha T., Kapur M., 2021: *When Problem Solving Followed by Instruction Works: Evidence for Productive Failure*. Review of Educational Research, 91(5), 761–798.

Song Y., Kapur M., 2017: *How to Flip the Classroom – "Productive Failure or Traditional Flipped Classroom" Pedagogical Design?* Journal of Educational Technology & Society, 20(1), 292–305.

Wei J., Wang X., Schuurmans D., Bosma M., Ichter B., Xia F., Chi E., Le Q., Zhou D., 2023: *Chain-of-Thought Prompting Elicits Reasoning in Large Language Models*. https://arxiv.org/abs/2201.11903

Weidinger L., Mellor J., Rauh M., Griffin C., Uesato J., Huang P.-S., ..., Gabriel I., 2021: *Ethical and social risks of harm from language models*. arXiv preprint arXiv:2112.04359. https://arxiv.org/abs/2112.04359

Ziegler E., Trninic D., Kapur M., 2021: *Micro productive failure and the acquisition of algebraic procedural knowledge*. Instructional Science, 49(3), 313–336.

## APPENDIX

List of 45 publications included in the meta-analysis [Sinha, Kapur, 2021]. Within these 45 articles, 53 studies were identified, comprising a total of 166 experimental comparisons.

### Reference List for N = 45 Articles Included in the Meta-Analysis[5]

1. Arrington, T. L. (2018). *Productive Failure: Examining the Impact of Need for Cognition and Cognitive Flexibility on Conceptual Learning in Chemistry* (Doctoral dissertation, The Florida State University).
2. Belenky, D. M., & Nokes-Malach, T. J. (2012). Motivation and transfer: The role of mastery-approach goals in preparation for future learning. *Journal of the Learning Sciences, 21*(3), 399–432.
3. Cernusca, D., & Mallik, S. (2018). Making failure productive in an active learning context: Improved student performance and perceptions in a pharmaceutics chemistry course. *Quarterly Review of Distance Education, 19*(2), 37–50.
4. Chase, C. C., & Klahr, D. (2017). Invention versus direct instruction: For some content, it's a tie. *Journal of Science Education and Technology, 26*(6), 582–596.
5. Chen, D. W. (2018). *An investigation of pedagogical interventions within the productive failure methodology* (Doctoral dissertation, Georgia Institute of Technology).
6. Chowrira, S. G., Smith, K. M., Dubois, P. J., & Roll, I. (2019). DIY productive failure: Boosting performance in a large undergraduate biology course. *NPJ Science of Learning, 4*(1), 1.
7. Coppens, L. C., Hoogerheide, V., Snippe, E. M., Flunger, B., & van Gog, T. (2019). Effects of problem–example and example–problem pairs on gifted and nongifted primary school students' learning. *Instructional Science, 47*(3), 279–297.
8. DeCaro, M. S., & Rittle-Johnson, B. (2012). Exploring mathematics problems prepares children to learn from instruction. *Journal of Experimental Child Psychology, 113*(4), 552–568.
9. DeCaro, D. A., DeCaro, M. S., & Rittle-Johnson, B. (2015). Achievement motivation and knowledge development during exploratory learning. *Learning and Individual Differences, 37*, 13–26.
10. Fukaya, T., Uesaka, Y., & Ichikawa, S. I. (2019). Investigating the effects of Thinking after Instruction approach. *Educational Technology Research, 41*(1), 1–11.
11. Fyfe, E. R., DeCaro, M. S., & Rittle-Johnson, B. (2014). An alternative time for telling: When conceptual instruction prior to problem solving improves mathematical knowledge. *British Journal of Educational Psychology, 84*(3), 502–519.
12. Geel, K. V., Kok, E. M., Aldekhayel, A. D., Robben, S. G., & van Merriënboer, J. J. (2019). Chest X-ray evaluation training: Impact of normal and abnormal image ratio and instructional sequence. *Medical Education, 53*(2), 153–164.
13. Hofer, S. I., Schumacher, R., Rubin, H., & Stern, E. (2018). Enhancing physics learning with cognitively activating instruction: A quasi-experimental classroom intervention study. *Journal of Educational Psychology.*

[5] Source: Sinha, Kapur, 2021

14. Hsu, C. Y., Kalyuga, S., & Sweller, J. (2015). When should guidance be presented in physics instruction? *Archives of Scientific Psychology, 3*(1), 37.
15. Jacobson, M. J., Markauskaite, L., Portolese, A., Kapur, M., Lai, P. K., & Roberts, G. (2017). Designs for learning about climate change as a complex system. *Learning and Instruction, 52*, 1–14.
16. Jarosz, A. F., Goldenberg, O., & Wiley, J. (2017). Learning by invention: Small group discussion activities that support learning in statistics. *Discourse Processes, 54*(4), 285–302.
17. Kapur, M. (2014). Productive failure in learning math. *Cognitive Science, 38*(5), 1008–1022.
18. Kapur, M., & Bielaczyc, K. (2011). Classroom-based experiments in productive failure. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 33, No. 33).
19. Kapur, M., & Bielaczyc, K. (2012). Designing for productive failure. *Journal of the Learning Sciences, 21*(1), 45–83.
20. Kapur, M. (2010). Productive failure in mathematical problem solving. *Instructional Science, 38*(6), 523–550.
21. Kapur, M. (2011). A further study of productive failure in mathematical problem solving: Unpacking the design components. *Instructional Science, 39*(4), 561–579.
22. Kapur, M. (2012). Productive failure in learning the concept of variance. *Instructional Science, 40*(4), 651–672.
23. Kerrigan, J. (2018). *Productive failure in the flipped mathematics classroom* (Doctoral dissertation, Rutgers University–Graduate School of Education).
24. Kulasegaram, K., Axelrod, D., Ringsted, C., & Brydges, R. (2018). Do one then see one: Sequencing discovery learning and direct instruction for simulation-based technical skills training. *Academic Medicine, 93*(11S), S37–S44.
25. Lai, P. K., Portolese, A., & Jacobson, M. J. (2017). Does sequence matter? Productive failure and designing online authentic learning for process engineering. *British Journal of Educational Technology, 48*(6), 1217–1227.
26. Lamnina, M., & Chase, C. C. (2019). Developing a thirst for knowledge: How uncertainty in the classroom influences curiosity, affect, learning, and transfer. *Contemporary Educational Psychology, 59*, 101785.
27. Loehr, A. M., Fyfe, E. R., & Rittle-Johnson, B. (2014). Wait for it… Delaying instruction improves mathematics problem solving: A classroom study. *The Journal of Problem Solving, 7*(1), 5.
28. Loibl, K., & Rummel, N. (2014a). Knowing what you don't know makes failure productive. *Learning and Instruction, 34*, 74–85.
29. Loibl, K., & Rummel, N. (2014b). The impact of guidance during problem-solving prior to instruction on students' inventions and learning outcomes. *Instructional Science, 42*(3), 305–326.
30. Matlen, B. J., & Klahr, D. (2013). Sequential effects of high and low instructional guidance on children's acquisition of experimentation skills: Is it all in the timing? *Instructional Science, 41*(3), 621–634.
31. Marei, H. F., Donkers, J., Al-Eraky, M. M., & van Merrienboer, J. J. (2017). The effectiveness of sequencing virtual patients with lectures in a deductive or inductive learning approach. *Medical Teacher, 39*(12), 1268–1274.
32. Mazziotti, C., Loibl, K., & Rummel, N. (2015). Collaborative or individual learning within productive failure: Does the social form of learning make a difference? In *CSCL 2015 Proceedings* (pp. 570–575). ISLS.
33. Mazziotti, C., Rummel, N., Deiglmayr, A., & Loibl, K. (2019). Probing boundary conditions of productive failure and analyzing the role of young students' collaboration. *NPJ Science of Learning, 4*(1), 2.

34. Newman, P. M., & DeCaro, M. S. (2019). Learning by exploring: How much guidance is optimal? *Learning and Instruction, 62*, 49–63.
35. Raes, A., Vanneste, P., Vens, C., & Depaepe, F. (2018). Teaching for versus through problem solving: Impact on teaching and learning. In *CSCL 2018 Proceedings*. ISLS.
36. Schalk, L., Schumacher, R., Barth, A., & Stern, E. (2018). When problem-solving followed by instruction is superior to the traditional tell-and-practice sequence. *Journal of Educational Psychology, 110*(4), 596.
37. Schneider, B., & Blikstein, P. (2018). Tangible user interfaces and contrasting cases as a preparation for future learning. *Journal of Science Education and Technology, 27*(4), 369–384.
38. Schwartz, D. L., & Martin, T. (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction. *Cognition and Instruction, 22*(2), 129–184.
39. Schwartz, D. L., Chase, C. C., Oppezzo, M. A., & Chin, D. B. (2011). Practicing versus inventing with contrasting cases: The effects of telling first on learning and transfer. *Journal of Educational Psychology, 103*(4), 759.
40. Song, Y. (2018). Improving primary students' collaborative problem solving competency in project-based science learning with productive failure instructional design in a seamless learning environment. *Educational Technology Research and Development, 66*(4), 979–1008.
41. Song, Y., & Lung, K. M. (2017). Improving primary students' problem solving skills in science learning in a seamless learning environment. In *Proceedings of the 25th International Conference on Computers in Education* (pp. 671–675). APSCE.
42. Steenhof, N., Woods, N. N., Van Gerven, P. W., & Mylopoulos, M. (2019). Productive failure as an instructional approach to promote future learning. *Advances in Health Sciences Education, 24*(5), 979–990.
43. Tam, K. (2017). *Examining Productive Failure Instruction in Dental Ethics.*
44. Vitale, J. M., Applebaum, L., & Linn, M. C. (2019). Coordinating between graphs and science concepts: Density and buoyancy. *Cognition and Instruction, 37*(1), 38–72.
45. Weaver, J. P., Chastain, R. J., DeCaro, D. A., & DeCaro, M. S. (2018). Reverse the routine: Problem solving before instruction improves conceptual knowledge in undergraduate physics. *Contemporary Educational Psychology, 52*, 36–47.