

Market Insights by Machines: Using LLMs for Survey Response and Benchmark Generation, including LLM-as-a-Judge Evaluation

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Abstract

When conducting market research, we are confronted with high amount of text data from different online sources, besides others. In this final project it is analyzed, in which way Natural Language Processing (NLP) and especially Large Language Models (LLMs) can support as an augmentation to human expertise. Three different fields are investigated: First, the LLMs are prompted to get their responses to specific market analysis topics, as a basis to check how useful and correct the data retrieved from the LLMs themselves is (purely from training data and fine-tuning). Secondly, to evaluate the responses from the LLMs by comparing to a reference using the LLM-as-a-Judge approach. Third, to use LLMs for aggregating a single benchmark from several references. Depending on the model used, it is impressive how well the LLM responses fit to the responses from deep research agents, which are taken as a reference. The proposed LLM-as-a-Judge is capable of returning a rating in a specified numeric scale including the rationale for this rating, what makes the rating well understandable. The aggregated benchmark, what is the combination of the delivered references, is generated by an LLM. Beside the aggregation responses themselves, it is sufficiently explained which content portion comes from which reference(s) and where the differences between the references are. Due to extensive amount of text pages, the complete benchmark responses are put into the ANNEX instead of the report main part. Therewith, if from business perspective it is desired to consult the responses from the deep research agents used as a reference, they are accessible as still a part of the same document. A non-expert in market analysis and the semiconductor market (which was analyzed in this project, as an example market), probably would at least partly rely on one or more deep research agent as information source.

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Certificate of Advanced Studies in Natural Language Processing (CAS NLP)

Continuing Education Programs in Extended Intelligence

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1 Introduction

The motivation of this project is to investigate about how to use generative AI for information gathering, processing and analysis for the market analysis use case. This means in the context here to analyze how Natural Language Processing NLP, consisting of Natural Language Understanding NLU and Natural Language Generation NLG, and in this case concretely LLMs, can be used to complement humans in such research and data analysis intense tasks, for increasing efficiency and also quality. It is regarded as an augmentation to human expertise, where at least the strategic decisions, the personal dialogue with clients, visiting relevant conferences and orchestration of collectives consisting of people and machines have to stay: Human-in-the-loop will remain as a crucial part. Machines can bring relevant support as soon as where it is about huge amounts of data to be collected and analyzed for trends in the form of published online news (company and research institutions websites, social media, patent databases). In dynamic situations the process has to be repeated periodically. As an example, in this project the market analysis is deepened for the semiconductor market in combination with the use of X-ray sources, X-ray tubes and X-ray generators in the semiconductor manufacturing process. It is desired to propose methods, which can be used also for other markets and/or products, with minimal changes required. Therewith, survey questions, as they are called here, and their translation into user prompts is designed as generic as possible.

The goal is, besides in the ideal case gathering some relevant content, to make the choice of the approaches and methods ideally reusable also for analysis of other markets and products, or some parts to be used even for completely different use cases. It is worked with the so called Comet SmartLab infrastructure, as far as possible and meaningful. There, a computer equipped with a relatively powerful GPU is available, which is used as a shared resource inside the company, what means many persons have access to it.

The final project is the last part of the CAS NLP program, after modules 1 to 6, each of them consisting of lectures, hands-on sessions and related project works. As the project is built around prompting techniques for LLMs, it can be seen mostly rooted in the topics from module 4, where it was about the transformers architecture, and specially the lectures about LLMs with transformers as the core.

2 Approach and Methods

For the use case of market analysis described above, there is no data available that could be analyzed directly using NLP methods. Therefore, prompt engineering is performed, instead of fine-tuning or retrieval augmented generation (RAG) what are other common methods when working with LLMs. To have a more comfortable workflow, it is desired to use the LLMs with an API (application programming interface). This can be done by subscribing for a service from a company which offers API access to cloud hosted LLMs, or by hosting LLMs on own hardware. For this project, the second one is chosen. Besides that at Comet there is a shared resource with a relatively powerful GPU as a part of the so called SmartLab, hosting own LLMs also has following advantages: Customization and more flexibility, privacy and security, compliance and cost control. When working with LLMs, one should also be aware of the limitations as e.g. hallucinations and bias, specially if no fine-tuning or RAG is performed.

2.1 Ollama

Ollama is a local, open-source tool that allows users to run LLMs on their own computers. It simplifies the process of downloading, managing, and deploying open-source LLMs, providing a platform for local AI development and interaction without relying on cloud services. As mentioned above, Ollama runs models on the user's computer, ensuring that data and interactions remain private and secure. It is freely available and allows users to leverage open-source LLMs without cloud dependencies. The API allows developers to integrate LLMs into their applications. Ollama is an open-source project with a growing community, fostering collaboration and the sharing of models and best practices. See Ollama API Doc 2025 for more details regarding the usage of the Ollama API.

The following table gives an overview of the models which were used in this project, the 'small' ones on host 1, what is an average laptop, and the 'midsize' models on host 2, what is a computer in Comet SmartLab with a relatively powerful GPU relative to average PCs.

Model name	Publisher	Host
deepseek-r1:1.5b	DeepSeek	1
deepseek-r1:32b	DeepSeek	2
gemma3:1b	Google	1
gemma3:27b-it-q4_K_M	Google	2
qwen3:1.7b	Alibaba Cloud	1
qwen3:30b	Alibaba Cloud	2
smollm2:1.7b	HuggingFace	1

Table 1: Models used: For DeepSeek-R1, Gemma3 and Qwen3 for each a 'small' and a 'midsize' model was used, for smollm2 only the one with 1.7b parameters, which is the biggest smollm2 model

To learn more about each individual model, it can be started with the Ollama overview page per model, where a short description and usage hints are given, for some of them also links to e.g. papers are included, see Ollama DeepSeek Overview Webpage 2025; Ollama Gemma3 Overview Webpage 2025; Ollama Qwen3 Overview Webpage 2025; Ollama Smollm2 Overview Webpage 2024.

In the ANNEX F more information about the Hardware where the Ollama models are running on single-GPU is given, for host 1 and 2. For testing while code development, working with the 'small' models is fine. When working with the bigger models in the range 30b, host 2 is used. Having two hosts available at the same time, also helps to parallelize tasks, as e.g. to run LLM-as-a-judge (what is quite computation-costly due to long prompts and bigger models due to performance) with the bigger models while analyzing and plotting results using the small ones.

The host can be selected in the parameter file:

```

if host == 1:
    OLLAMA_HOST = "http://localhost:11434"
    models = ['deepseek-r1:1.5b', 'gemma3:1b', 'qwen3:1.7b', 'smollm2']
elif host == 2:
    OLLAMA_HOST = "https://ollama-ha.comet-lab.group"
    models = ['deepseek-r1:32b', 'gemma3:27b-it-q4_K_M', 'qwen3:30b']
else:
    print('please check your host definition in parameters.py')

```

Figure 1: Snippet from *parameters.py*, where the host is selected: Host one is a laptop where the small models are running, and host 2 is a computer in Comet SmartLab with a more powerful GPU where the 'midsize' models are running

Other parameters handed over to Ollama are e.g. temperature (randomness of predictions), the documentation of possible model parameterization can be read here: [Ollama Parameter Doc 2025](#).

2.2 Market Survey Prompt Collection

It is desired, to design the prompts in a generic way, as far as possible, that ideally in the future it could also be used for market research of other markets and other products: Market and products are defined as constants. As a prompting technique, a combination of instruction prompting is used for the user prompts, what leads to detailed, step-by-step instructions => clarifies the task and brings structure, and for the system prompt a role-based prompt is used, what clarifies the task and simulates expertise. Doing so, the quality of instructions is important, in general the number of tokens is increased.

```

# used in generic prompts
MARKET = "semiconductor market"
PRODUCTS = "X-ray sources, X-ray tubes and X-ray generators"

```

Figure 2: Snippet from *parameters.py*, where market and products are defined, as a basis for the generic prompts

Below, the system and user prompts are shown, a nicer presentation of the prompts can be seen in ANNEX B.

```

from parameters import MARKET, PRODUCTS
# insert {MARKET}; {PRODUCTS}

system_prompt = f"You are a helpful assistant with in-depth knowledge of the
{MARKET} and related manufacturing processes. Please help me to conduct a market
analysis for the {MARKET} relevant to a company that develops and supplies
{PRODUCTS}. Please answer briefly and concisely. If possible, use bullet points
only."

user_prompts = [
    "1: Name all the steps in semiconductor manufacturing, numbered, and state
    whether they are the "Back End of Line" (BEOL) or the "Front End of Line" (FEOL).
    2: In which of these steps are X-rays used and why - 2.a) today and 2.b) possibly
    in the future",
    f"Which companies supply the semiconductor manufacturers with {PRODUCTS}, and
    which companies supply the OEMs active in the {MARKET} with {PRODUCTS}? Which are
    the 5 largest semiconductor manufacturers?",
    "Which inspection technologies other than X-ray are used in which steps of |
    semiconductor manufacturing? For each of these processes: Why not X-ray? What are
    the disadvantages of the current non-X-ray method and what would be the advantages
    of using X-rays instead?",
    "Tell me more about X-ray lithography XRL, X-ray diffraction XRD and X-ray
    fluorescence XRF. What are the opportunities, requirements and challenges
    (technical and economical)?",
    f"What else could be of interest with regard to the {MARKET} for a company that
    develops and sells {PRODUCTS}?",
    f"What are the trends and market potential of X-ray inspection in the {MARKET}?
    What are the hurdles to entering the {MARKET} when offering {PRODUCTS}?",
    f"Conduct a {MARKET} analysis, relevant to a company that develops and offers
    {PRODUCTS}, with all the steps that usually go with it.",
    "Who are you and which role are you playing?",
]

```

Figure 3: In `llm_survey_prompt_collection.py`, the system and user prompts are defined. As far as possible it is done using placeholders for market and products

2.3 Survey Response Generation

As responses to a collection of questions from different models with a defined set of temperatures is collected, it is called survey. With this, it can be evaluated at a later stage, how “grounded” the simple LLMs are, with proprietary deep research agents as a benchmark. It is interesting to learn about the sensitivity of performance depending on model (type & size), prompt, and temperature (randomness of predictions: low vs high => deterministic/predictable vs creative writing): `survey_response_acquisition.py` loops through all models (available on selected host), user prompts and temperatures (0 and 1, min. and max. with Ollama API, to see the extreme values), and finally calls a save routine to store the response in a json file.

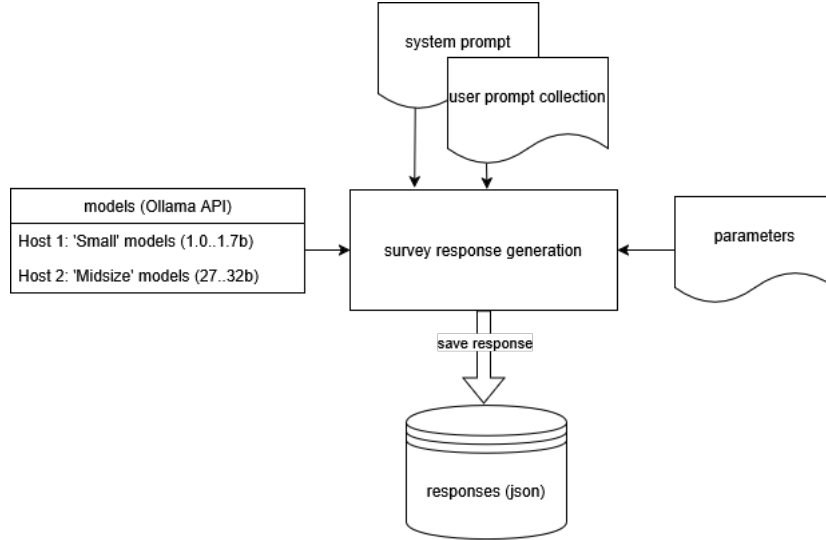


Figure 4: Overview of survey response generation, with the available models, prompts and parameters as inputs, and as an output the response saved as a json file

2.4 Benchmark

Deep research agents

The free-of-charge versions of proprietary deep research agents are used. In simple words, deep research agents are LLMs augmented with a websearch tool. This allows access to actual data, delivers the sources, and could be called grounding. The responses from the three deep research agents are stored in a json file using *save_benchmark_data.py*, same structure as the responses from the Ollama models. See ANNEX B for full response texts. For getting the benchmark, the survey prompt collection is combined into one prompt as an input for the deep research agents. The following table gives an overview about the three deep research agents used:

Name	Model Version	Publisher	Mode
ChatGPT	GPT 4.1 mini	OpenAI	Deep Research
Gemini	Gemini 2.5 flash	Google	Deep Research
Perplexity	GPT 3.5	Perplexity	Deep Research

Table 2: Deep research agents used: ChatGPT, Gemini and Perplexity, all in 'deep research' mode

LLM-generated benchmark aggregation

The benchmark aggregation creates one LLM-generated benchmark from the three references given using *aggregation.py*. The aggregation response is saved together with the information which references were used and which model and temperature was used for generating the aggregation. The number of tokens, specially on the input, resp. from the prompt, is analyzed because it can get pretty long due to the judge prompt with the three reference responses plus the aggregation prompt. See ANNEX C for the full response texts.

```

multi_reference_aggregation_prompt = """
You will be given one survey question and three reference answers.
Your task is to aggregate the three reference answers into one ground truth answer.
This ground truth will be used to evaluate responses from simple LLMs.

Provide your feedback as follows:

Feedback::
Aggregation: (your rationale for the aggregated answer, as a text)

You MUST provide 'Aggregation:' in your answer, and nothing else.

Now here are the question and answer.

Question: {question}
Reference Answer 1: {answer1}
Reference Answer 2: {answer2}
Reference Answer 3: {answer3}

Feedback::
Aggregation: """

```

Figure 5: Multi-reference aggregation prompt, from *aggregation.py*: Question and three reference answers are delivered, the LLM is asked to return the combined, resp, aggregated, response respecting all three references.

The following block diagram shows the interconnection of benchmark acquisition and LLM-generation of the aggregated benchmark.

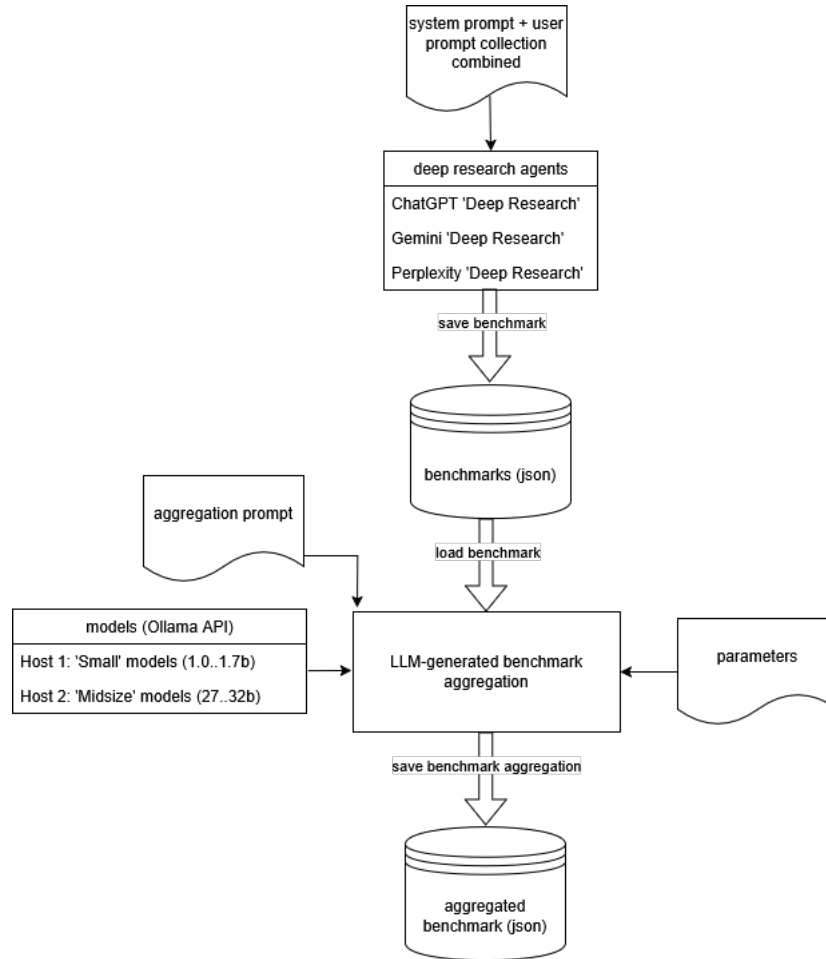


Figure 6: Overview of LLM-generated benchmark aggregation, with the benchmark coming from deep research agents, available models on Ollama, aggregation prompt and parameters as inputs, and as an output the aggregated benchmark saved as a json file

2.5 LLM-as-a-Judge Evaluation

LLM-as-a-Judge has shown good performance in evaluating LLMs with human judgments as a benchmark. As an introduction to LLM-as-a-Judge, the following references are seen as useful: Aymeric Roucher, LLM Judge 2024; Quinn Leng et al. 2023; Lianmin Zheng et al. 2023. It is recommended to use a low temperature, e.g. 0.1, what was then also used in the investigations shown below. In addition, LLM-as-a-Judge performs better if not the smallest models are used. Therefore, after only a quick test with the small models, it was switched to the 'midsize' models used as a judge. Due to resource reasons, for this project the comparison to human judgment is not done, just a few plausibility checks with positive result. *evaluation.py* contains the LLM-as-a-judge, *run_all_evaluation.py* runs the evaluation over a set of pre-defined responses.

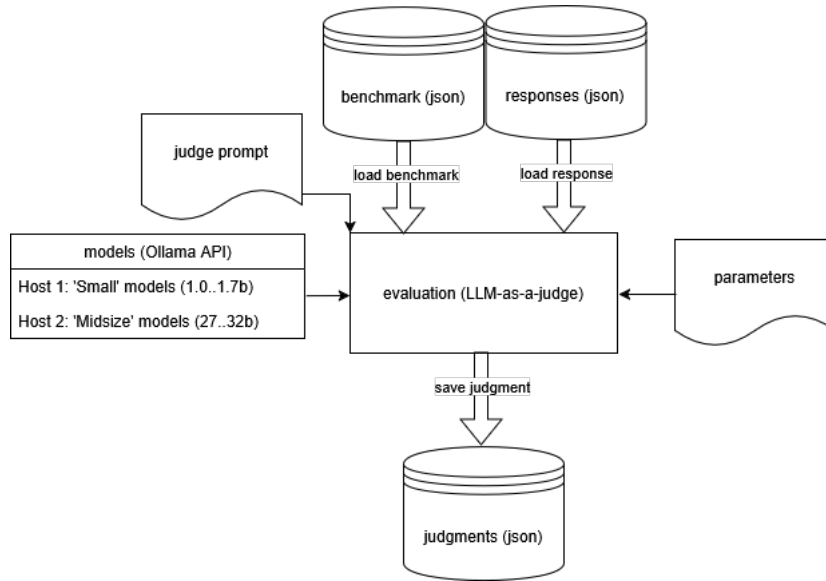


Figure 7: Overview of LLM-as-a-Judge evaluation, with the available models, benchmark and LLM responses, judge prompt and parameters as inputs, and as an output the judgment saved as a json file

The design of the judge prompt is inspired by Aymeric Roucher, LLM Judge 2024; Lianmin Zheng et al. 2023, especially the scale of the rating and wording, respectively, and adapted to the use case shown in this report.

```

# Reference Guided Judge Prompt
JUDGE_PROMPT = """
Please act as an impartial judge and evaluate the quality of the response provided
by an AI assistant to the user question displayed below, with a reference answer to
be used as a benchmark. Your evaluation should consider factual correctness,
relevance, accuracy and helpfulness, again guided by the reference. You will be
given a reference answer and the assistant's answer. Begin your evaluation by
comparing the assistant's answer with the reference answer.
Identify and correct any mistakes in the assistant's answer, according to the
reference answer. Avoid any position biases and ensure that the order in which the
responses were presented does not influence your decision. Do not allow the length
of the responses to influence your evaluation. Do not favor certain names of the
assistants. Be as objective as possible.

Your task is to provide a 'total rating' scoring how well the assistant's answer
answers the user concerns expressed in the user question, guided by the given
reference answer.
Give your answer on a scale of 1 to 4, where 1 means that the assistant's answer is
not helpful at all, and 4 means that the assistant's answer completely and
helpfully addresses the user's question, all guided by the reference answer.

Here is the scale you should use to build your answer:
1: The assistant's answer is terrible: completely irrelevant to the question asked,
or very partial
2: The assistant's answer is mostly not helpful: misses some key aspects of the
question
3: The assistant's answer is mostly helpful: provides support, but still could be
improved
4: The assistant's answer is excellent: relevant, direct, detailed, and addresses
all the concerns raised in the question and answered in the reference answer

After providing your explanation, output your final verdict by strictly following
this format:

Feedback:::
1.) Total rating: (your rating, as a number between 1 and 4)
2.) Evaluation: (your rationale for the rating, as a text)

You MUST provide values for '1.) Total rating:' and '2.) Evaluation:' in your
answer.

Now here are the question, reference answer and the assistant's answer.

[User Question]
{question}

[The Start of Reference Answer]
{ref_answer}
[The End of Reference Answer]

[The Start of the Assistant's Answer]
{answer}
[The End of the Assistant's Answer]

Provide your feedback. If you give a correct rating, you'll get whatever you want.
Feedback:::
1.) Total rating
2.) Evaluation:
"""

```

Figure 8: Reference guided judge prompt, from *evaluation.py*

Some trial and error was needed to compose the judge prompt, as some models initially did not give the rating as a number but only the text-form evaluation. This was solved by explicit formulation, here e.g. with the '...MUST contain...', see above. The judgment is saved into a json file: The total rating is saved as a number into a separate field in the json file, besides the evaluation text, judge model and judge temperature.

3 Experimental Results

Following Python packages are used for analyzing and plotting the judgments: Pandas (data analysis), Matplotlib (visualization) and Seaborn (statistical data visualization).

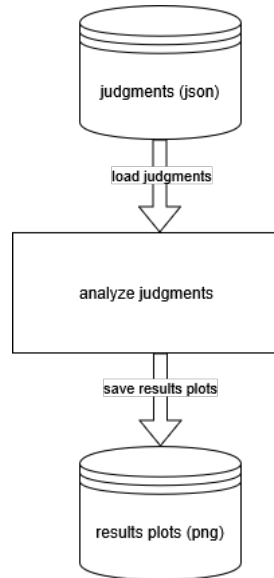


Figure 9: Running *analyze_judgments.py*, the judgments are loaded, analyzed and the results plots are saved as a png image

About interpretation of judgment result: Not fully about good or bad answer regarding system and user prompt following, it is more about how close the answer is relative to the reference. Nevertheless, the LLM-as-a-Judge recognized the problem and reacted with low rating in a specific test, where the response was given to the wrong question. The plot below gives an overview of the results, for all user prompts, models and both temperatures. As a judge two 'midsize' models are used, gemma3:27b-it_q4_K_M and qwen3:30b. As a reference, ChatGPT in Deep Research mode was taken.

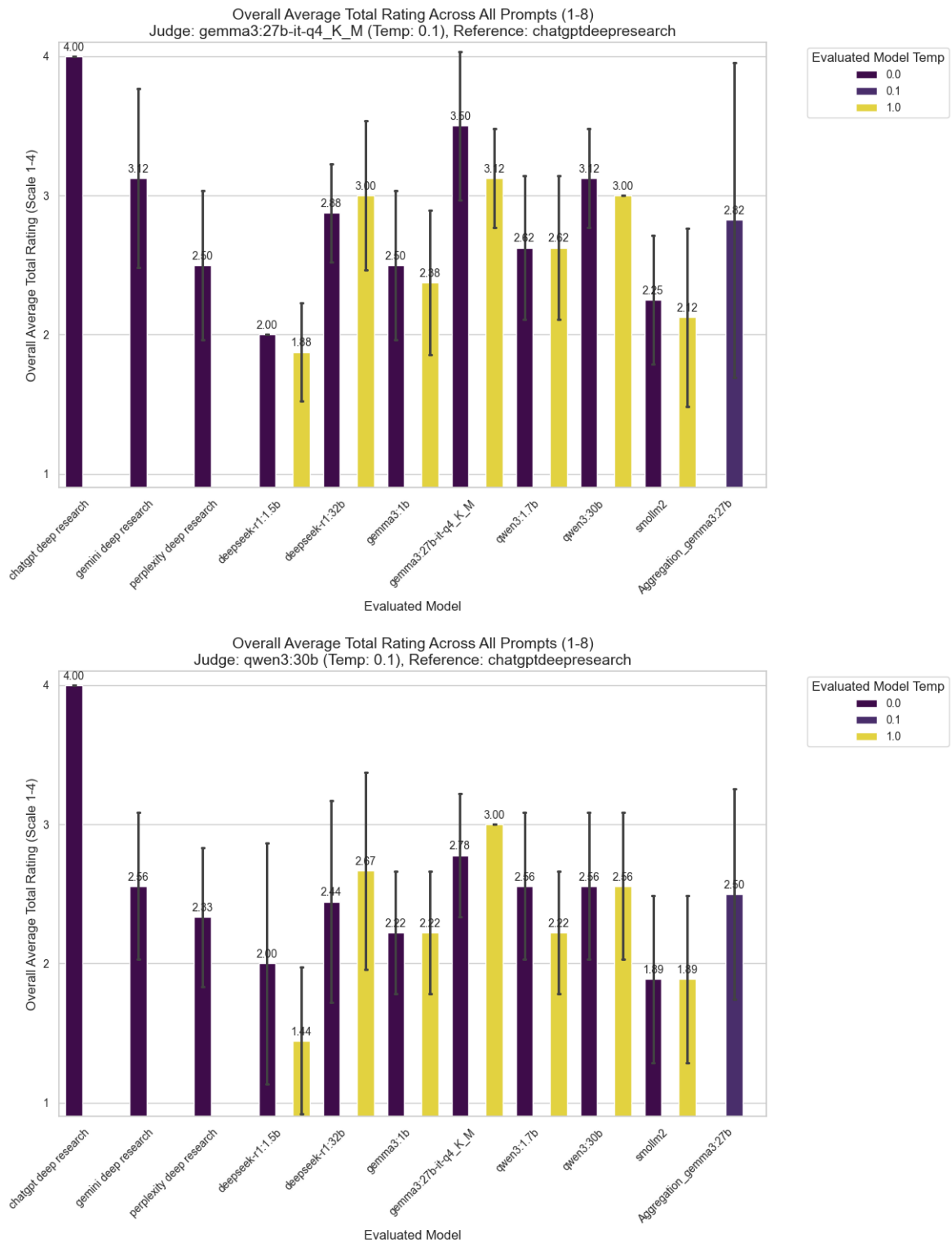


Figure 10: The plot shows the overall rating for all user prompts 1-8 for all models and both temperatures used. The standard deviation is indicated, to give an idea about model performance evaluation for all user prompts. The aggregated benchmark was generated with temp = 0.1, deep research agents saved with temp = 0, what obviously is just a dummy

The judgments for each individual prompt are not shown here, but in ANNEX D.

Discussion of results

- The temperature parameter has not the expected effect (with temperature 1 a significantly lower performance than with temperature 0 was expected)
- Small vs 'midsize' models for response generation: The small models responses in average are not judged much lower than those of the 'midsize'
- From the small models, qwen3:1.7b is the only one which recognizes when the assistant and reference answers are 100% the same(!) => clear confirmation to use 'midsize' models as a judge
- Furthermore, the small models do bad differentiation, many responses get the same rating.
- Therefore, only the judgments of the midsize models Gemma3:27b and Qwen3:30b are shown, no small model as judge
- 'Midsize' models as judge compared: It looks like Gemma3 is more "positive" resp. "less strict" compared to Qwen3
- Consistency I: Repetition of judgment with same response files with same judge models with one question (prompt 1, qwen3:30b as a judge), see ANNEX D
- Consistency II: Model performance for all survey question responses compared, see plot above
- System prompt following: Deepseek-R1 seems to ignore it completely, can be seen in rating and checked in response file

4 Conclusion

The results show, that depending on model and prompting technique, with open source, locally running LLMs, specific information regarding the semiconductor market can be collected in a quite good quality. Furthermore, aggregated benchmarks out of several grounded references were generated by an LLM, with explanation which part comes from which reference and where the differences in the references are. Finally, both the LLM survey responses and the aggregated benchmark are evaluated using the LLM-as-a-Judge approach. Those investigations could be useful for other tasks, with minor adaptations in code.

What has not been performed in this project, and could be seen as a limitation of approach, is the missing human evaluation of responses (as a benchmark for LLM-as-a-Judge), and also missing human curated ground truth. Both are not performed due to resource reasons and also due to the question of reliable vs ambiguous information sources. Eventually the same sources, what are the deep research agents, would have been used as for creating the three references.

5 Acknowledgments

- to the director of studies, PD Dr. Sigve Haug, for organizing this CAS in NLP and the whole Continuing Education Program in Extended Intelligence;
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- my employer Comet Group, Industrial X-ray Modules Division and corresponding senior management team members, for the sponsorship and the discussions about business relevant use cases and from content perspective in which fields new insights would be interesting;
- my family for the support and giving me the freedom of investing the needed hours.

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6 ANNEX A - Link to repository

The code which was developed for this project (Python files), the generated json files (LLM responses, benchmarks, evaluations), results plots and this report can be found here: <https://github.com/sandrowiedmer/NLP-Final-Project>

7 ANNEX B - Benchmark from deep research agents

The sources in the benchmark files below were removed, responses incl weblink sources, because just the content of the responses is used as a reference. For generating the following benchmark data, the free-of-charge versions of proprietary deep research agents are used. It was saved on 2025-05-28, to have from then on a fixed reference. The system prompt and the eight user prompts introduced in the main part, are taken together into one prompt as an input for the deep research agents:

“You are a helpful assistant with in-depth knowledge of the semiconductor market and related manufacturing processes. Please help me to conduct a market analysis for the semiconductor market relevant to a company that develops and supplies X-ray sources, X-ray tubes and X-ray generators. Please answer briefly and concisely. If possible, use bullet points only. Refer to the Roman numbering in the questions in your answers.

- I) 1: Name all the steps in semiconductor manufacturing, numbered, and state whether they are the “Back End of Line” (BEOL) or the “Front End of Line” (FEOL). 2: In which of these steps are X-rays used and why - 2.a) today and 2.b) possibly in the future
- II) Which companies supply the semiconductor manufacturers with X-ray sources, X-ray tubes and X-ray generators, and which companies supply the OEMs active in the semiconductor market with X-ray sources, X-ray tubes and X-ray generators? Which are the 5 largest semiconductor manufacturers?
- III) Which inspection technologies other than X-ray are used in which steps of semiconductor manufacturing? For each of these processes: Why not X-ray? What are the disadvantages of the current non-X-ray method and what would be the advantages of using X-rays instead?
- IV) Tell me more about X-ray lithography XRL, X-ray diffraction XRD and X-ray fluorescence XRF. What are the opportunities, requirements and challenges (technical and economical)?
- V) What else could be of interest with regard to the semiconductor market for a company that develops and sells X-ray sources, X-ray tubes and X-ray generators?
- VI) What are the trends and market potential of X-ray inspection in the semiconductor market? What are the hurdles to entering the semiconductor market when offering X-ray sources, X-ray tubes and X-ray generators?
- VII) Conduct a semiconductor market analysis, relevant to a company that develops and offers X-ray sources, X-ray tubes and X-ray generators, with all the steps that usually go with it.
- VIII) Who are you and which role are you playing?”

7.1 ChatGPT (‘Deep Research’ mode)

I. Semiconductor Manufacturing Steps (FEOL vs BEOL)

1. Wafer Preparation (pre-FEOL): Crystal growth, wafer slicing, polishing and cleaning (before front-end processes). (Not FEOL or BEOL; preparatory stage.)
2. Oxidation / Thin-Film Deposition (FEOL): Grow or deposit thin dielectric films (SiO_2 , nitrides) on wafer surfaces. (FEOL – sets up surfaces for device layers.)
3. Lithography (FEOL): Coat with photoresist and use optical/EUV lithography to pattern features. (FEOL – defines device geometry.)
4. Etching (FEOL): Remove material (dry/wet etch) to create trenches, wells, and gate structures. (FEOL – shapes transistor features.)
5. Ion Implantation / Doping (FEOL): Implant dopant ions and anneal to form source/drain and well regions. (FEOL – creates transistor junctions.)

6. Gate Formation (FEOL): Deposit and pattern gate dielectric and gate electrode (polysilicon or metal). (FEOL – completes transistor gates.)
7. Silicidation (FEOL/BEOL interface): Form silicide contacts on source/drain and gate to reduce resistance. (Transition step after FEOL, before metallization.)
8. Inter-layer Dielectric Deposition (BEOL): Deposit dielectric layers (PMD/ILD) between metal layers; perform CMP planarization. (BEOL – isolates metal layers.)
9. Contact/Via Formation (BEOL): Etch holes in dielectric to form contacts and vias down to silicon or lower metal. (BEOL – enables vertical connections.)
10. Metal Deposition and Patterning (BEOL): Deposit metal (Al, Cu) and pattern each interconnect layer (Met1, Met2, ...) via lithography and etch or damascene. (BEOL – builds wiring stack.)
11. Passivation (BEOL): Add top dielectric/passivation layer and open bond pad windows. (BEOL – protects and finalizes wafer before test.)
12. Wafer Test (Post-Fab): Probe electrical functionality of individual chips on wafer (outside cleanroom). (Post-fab – not FEOL/BEOL.)
13. Dicing (Post-Fab): Saw or dice wafer into individual die. (Post-fab.)
14. Packaging (Post-Fab): Attach die to substrate or leadframe, wire-bond or flip-chip, mold/cap. (Post-fab.)
15. Final Test (Post-Package): Electrical/thermal testing of packaged ICs. (Post-fab.)

X-ray Usage – Current (2.a) and Future (2.b): Current: X-ray inspection/metrology is used mainly in back-end or analysis steps. For example, X-ray computed tomography (CT) and 3D X-ray inspection are widely used in advanced packaging to detect voids, misalignments, and defects in solder bumps, wire bonds, and multi-chip packages semiengineering.com. X-ray fluorescence (XRF/TXRF) and X-ray reflectivity (XRR) are used in FEOL for thin-film composition and thickness measurements (e.g. contamination, film uniformity) rigaku.com. X-ray diffraction (XRD) is used offline for wafer crystal orientation and strain measurement (e.g. verifying epitaxial layer quality).

Future Opportunities: Several steps could see more X-ray use. **Lithography (FEOL):** “X-ray lithography” (using soft X-rays) has been researched as a successor to EUV, requiring ultra-bright X-ray sources and specialized resists. If practical sources/masks were developed, XRL could enable finer features. **Metrology and Inspection:** X-ray methods (e.g. CD metrology via critical-dimension SAXS/X-ray, X-ray scatterometry) may expand in BEOL/CD-control, as X-rays can penetrate multilayer stacks. **In-situ monitoring:** X-ray sensing (e.g. X-ray reflectometry) might be integrated for real-time film thickness control. In advanced packaging, more inline X-ray CT is likely as packaging complexity grows semiengineering.com. The reason: X-rays uniquely image subsurface features non-destructively and can probe dense materials, offering 3D inspection that optical/SEM can’t semiengineering.com. The challenge is developing sufficiently fast, high-resolution X-ray tools that can be integrated into fabs.

II. Key Suppliers and Top Manufacturers

X-ray Source/Tube/Generator Suppliers to Semiconductor OEMs: Major X-ray component suppliers include Hamamatsu Photonics (Japan – microfocus tubes and detectors), Varex Imaging (USA – tubes and detector arrays), Oxford Instruments X-ray Technology (UK – tubes and sources) us.metoree.com, Rigaku / NSI (Japan/USA – custom miniaturized sources) rigaku.com, Moxtek (USA – thin-film X-ray sources and windows) thomasnet.com, Spellman High Voltage Electronics (USA – HV power supplies and X-ray generators) us.metoree.com, Gulmay (UK – X-ray generators/tubes), Excillum (Sweden – metal-jet X-ray sources), Nordson (DAGE) (USA – micro-focus X-ray tubes, see BrightHawk), Delta Electronics (Delta PA) (Taiwan – X-ray generator modules) and Matsusada Precision (Japan – HV power supplies for X-ray) deltaww.com us.metoree.com. These firms work closely with semiconductor equipment OEMs (e.g. NXE/EUV toolmakers, inspection system makers) to integrate X-ray sources and modules.

Top 5 Semiconductor Manufacturers (by output): The world’s largest chip-makers (fabs) are TSMC (Taiwan) – the leading pure-play foundry, Samsung Electronics (South Korea) – memory and foundry, Intel (USA) – IDMs/logic chips, SK Hynix (South Korea) – memory, and Micron

Technology (USA) – memoryinvestopedia.comevertiq.com. These account for a major share of global production and capital equipment spend; any tool vendor (including X-ray suppliers) will target their fabs.

III. Alternative Inspection Technologies vs. X-ray (by Process Step)

Photolithography (FEOL): Alternate: Optical scanners (smaller-wavelength DUV/EUV steppers) and scanning electron microscopy (CD-SEM) measure critical dimensions. Why no X-ray: Conventional X-ray imaging lacks the magnification and high-res optics for on-wafer patterning; resists and masks for XRL are not mature. Current drawbacks: Optical CD tools hit diffraction limits at sub-20nm, SEM inspection is slow and vacuum-intensive, scatterometry can struggle with complex stacks. X-ray advantages: X-ray beams could, in theory, pattern or inspect through multilayer stacks without planarization; future XRL could allow extremely fine resolution if sources/masks advance.

Etch / Thin-film Deposition (FEOL): Alternate: Ellipsometry, reflectometry, ellipsometric scatterometry and profilometry measure film thickness and etch depth; SEM/TEM analyze profiles offline. Why no X-ray: X-ray imaging (e.g. XRR) is used for film thickness offline, but inline X-ray profile requires complex alignment. Current drawbacks: Optical metrology often requires know-how models (scatterometry models can be complex), and can't easily measure high aspect-ratio profiles or buried layers. X-ray advantages: XRD/XRR can precisely measure layer thickness, density and uniformity; X-ray microscopy could reveal 3D etch profile non-destructively.

Chemical-Mechanical Planarization (CMP, FEOL): Alternate: In-situ film endpoint monitors (acoustic, motor torque) and post-CMP optical profilers check uniformity. Why no X-ray: Acoustic is effective at endpoint detection; X-ray would be bulky and less direct for slurry removal. Current drawbacks: Uniformity variations can be missed until post-CMP metrology; slurry particles cause occasional defects. X-ray advantages: CT could scan post-CMP wafer to detect subsurface defects (particles, voids) that optical can't see.

BEOL Dielectric/Metal Layers: Alternate: Optical CD-SEM, scatterometry, atomic force microscopy (AFM) for line-width; probe-based capacitance (PDA) for via integrity. Why no X-ray: Many metrology tools exist; introducing X-ray is costly and X-ray contrast between metal and dielectric can be low. Current drawbacks: Optical/SEM require direct line-of-sight; FIB/TEM is destructive sample prep. Complex 3D interconnects are hard to fully inspect. X-ray advantages: X-ray CT can see internal 3D structure of multilevel interconnects and through-silicon vias (TSVs) without de-layering, improving failure analysis. X-ray scatterometry (CD-SAXS) can measure periodic features nondestructively.

Packaging (Post-Fab): Alternate: AOI (automated optical inspection), acoustic microscopy, shearography. Why no X-ray: Actually, X-ray is used here widely for solder-bump inspection, void detection. Optical cannot see inside package; acoustic has limited penetration through metals. Current drawbacks: Without X-ray, hidden defects (voids, cracks) are missed until reliability tests. X-ray advantages: Already recognized as essential – 2D/3D X-ray CT detects voids, delamination, and wirebond issues in advanced packages semiengineering.com. This non-destructive capability greatly improves yield in multi-chip modules.

IV. X-ray Techniques in Semiconductor Processing (XRL, XRD, XRF)

X-ray Lithography (XRL): Applications: Long-sought technology to pattern sub-10nm features using high-energy photons. Research examples include synchrotron-based lithography and laser-plasma X-ray sources. Opportunities: Theoretically enables smaller feature sizes than EUV; no diffraction masks (proximity printing). Requirements: Extremely bright, stable X-ray sources (often synchrotron-like) and radiation-hard resists; precise mask/stencil alignment. Challenges: Building a practical 13nm-wavelength source (e.g. metal-jet, plasma) with throughput; lack of suitable resists and masks (no lens, requires rigid stencil masks). Economic viability is doubtful given EUV adoption and high tool costs. Outlook: Currently niche/R&D. (See reports on XRL research failures in scaling beyond EUV – no high-volume deployment.)

X-ray Diffraction (XRD): Applications: Characterizing crystal structure, orientation, strain in wafers, epitaxial films, and dies. Used for wafer mapping of crystallographic orientation (e.g.

crystal-cut verification), measuring lattice strain in strained-Si/SiGe, and analyzing defects. Opportunities: In-line HRXRD or X-ray topography tools could monitor epitaxial layer quality or stress after high-temperature steps. Eg. Rigaku's HRXRD tools for epi films rigaku.com. Requirements: Monochromatic X-ray sources, precise goniometers, detectors. Integration into fab is hard; often done in lab. Challenges: Slow scanning and alignment, sensitivity to small defects requires powerful sources. Advantage: Non-destructive, high precision for composition/strain, complementing electron methods.

X-ray Fluorescence (XRF): Applications: Non-destructive elemental/metallurgical analysis. TXRF is used for trace metal contamination on wafers; EDXRF/WDXRF measure thin-film composition and thickness (e.g. for barrier/seed layers, solder chemistry). For example, TXRF is standard for ultra-trace contamination metrology rigaku.com.

- Opportunities: Grow of in-line XRF sensors for real-time film monitoring (thickness, dopant uniformity). Use in failure analysis for composition of unknowns.
- Requirements: High-throughput miniature X-ray sources and sensitive detectors; vacuum control for TXRF.
- Challenges: Limit of detection (ppb levels require long integration); calibration standards; setup for each film type.
- Advantages: Element-specific, capable of analyzing heavy and light elements; penetrates layers for buried-interface analysis; can replace time-consuming wet-chem test.

V. Other Value-Chain Opportunities for X-ray Technology

- Advanced Packaging (3D-IC / Heterogeneous Integration): X-ray CT and 3D X-ray microscopy enable inspection of stacked-die packages, through-silicon vias (TSVs), micro-bump interconnects, and PoP (package-on-package) assemblies semiengineering.com. As AI and 5G chips rely on high-bandwidth memory (HBM) stacks, early detection of voids or misalignment by X-ray yields significant values semiengineering.com.
- Wafer-Level Packaging (WLP) & Fan-Out: X-ray systems can inspect die-attach and redistribution layer (RDL) interconnects at the wafer level to catch flip-chip solder voids or RDL cracks non-destructively.
- Die/Substrate Material R&D: In fabs and material suppliers, X-ray fluorescence and diffraction inspect raw materials (silicon wafers, deposition targets) for impurity levels and crystallinity. E.g. XRF for target doping uniformity; XRD for silicon wafer crystal defects.
- Failure Analysis (FA) and Reliability Labs: X-ray microscopy (3D XRM) and X-ray spectroscopy assist in FA of failed parts, providing 3D internal views without delayering. This is crucial as devices become more miniaturized. Sigray, Bruker, Hamamatsu, and others market such FA tools.
- Inline Process Control (Emerging): There is potential in embedding X-ray sensors into process tools – for example, monitoring etch uniformity or CMP endpoint using X-ray scattering, though such applications are experimental.

VI. X-ray Inspection Market Trends & Entry Hurdles

Market Trends: The X-ray inspection market is growing steadily (projected ~USD 1.2B by 2032 at ~5.4% CAGR globenewswire.com). 3D X-ray (CT) is expanding fastest, driven by advanced electronics and packaging needs globenewswire.com. Digital X-ray (detector-based) dominates, with AI-enabled analysis adding value globenewswire.com. In semiconductors specifically, demand is rising as feature sizes shrink and packaging grows in complexity (e.g. AI accelerators with HBM) semiengineering.com. OEMs now often require X-ray defect coverage alongside optical/acoustic inspection.

Global Potential: High-value semiconductor fabs in Asia, North America, and Europe represent key markets. The relentless push for zero-defect manufacturing makes X-ray inspection an attractive proposition for yield improvement. Advanced packaging fabs (foundries and OSATs) especially are adopting X-ray tools. Analysts note stringent quality standards across industries are “accelerating demand for X-ray inspection systems”globe.newswire.com, implying rising semiconductor adoption.

Hurdles to Entry: For a new X-ray technology supplier, barriers include:

- Technical qualification: Semiconductor OEMs have rigorous qualification processes; tools must meet extreme precision, cleanliness, and reliability specs.
- Integration challenges: Equipment must fit into cleanroom production (e.g. footprint, vibration, safety), and integrate with fab automation and software.
- Capital intensity: Developing X-ray systems (especially 3D CT) requires large R&D investment (e.g. custom sources, detectors, mechanics).
- Competition and incumbents: Established inspection vendors (Zeiss, KLA, Nordson, Yxlon, Hamamatsu, etc.) have entrenched relationships. A newcomer must demonstrate clear yield/ROI advantages.
- Economic: X-ray tools are expensive; fabs assess cost-of-ownership vs. yield gain. A startup must address cost, throughput, and maintenance challenges.

VII. Market Analysis for X-ray Technology Suppliers

- Market Size & Segmentation: The X-ray inspection systems market is segmented by technology (2D vs. 3D/CT, digital vs. film), by application (semiconductor, automotive, food, pharma, etc. – with semiconductor being a high-value niche), and by geography (Asia-Pacific leads semiconductor tool demand). Semiengineering/industry reports predict the market approaching \$1–1.5B by 2030globe.newswire.com, with a 3D-imaging segment growing fastest.
- Growth Drivers: Key drivers include miniaturization (smaller nodes require tighter inspection), advanced packaging (driving 3D CT), AI/5G (demand for high-performance chips), and Industry 4.0/AI analytics (integrating X-ray data into yield management). Stricter reliability and safety standards push semiconductor fabs to invest in better inspectionglobe.newswire.com.
- Trends: Digital transformation (AI/ML for defect recognition in X-ray images), increased use of compact microfocus sources, and multi-modal inspection (combining X-ray with acoustic or IR). Also, China’s semiconductor push may open new OEM opportunities, while U.S./EUR government support for chipmaking may boost spending.
- Competitive Landscape: Leading X-ray system makers span industries. For semiconductor inspection: Nordson (DAGE) and Teledyne / X-Ray (Thermo Fisher) in 2D/CT; Comet Yxlon (Germany) known for high-end CT; Hamamatsu (source/detectors); Nikon Metrology (microfocus X-ray CT); Bruker/Sigray (XRM for FA); plus general NDT leaders (Mettler-Toledo, Varex, etc.) now vying in electronics. Many are listed as key playersglobe.newswire.com. Suppliers of core components (Spellman, Oxford Inst., Rigaku/NSI, Moxtek) compete on tube/detector performance. Patents and proprietary optics (e.g. Bragg crystals) are important IP.
- Customer Needs: Semiconductor OEMs need extremely high-resolution, high-throughput, and reliable inspection tools. They demand sub-micron defect detection, 3D volumetric imaging of complex packages, rapid throughput (critical for inline use), and advanced analytics. Down-time must be minimal; maintenance/support in fabs worldwide is crucial. Suppliers often co-develop with OEMs to meet these specs.

- **Go-to-Market Strategies:** Successful vendors typically partner with established equipment OEMs or become approved suppliers to foundries/OSATs. They often focus on niche segments (e.g. wirebond inspection or micro-CT) before expanding. Demonstrating ROI via yield/loss reduction studies is key. Attending industry tradeshows (e.g. SEMICON, ASMC) and publishing application notes (as Gulmay did for X-ray usesgulmay.com) help gain credibility. Some form consortia (e.g. SEMATECH) or collaborate on standards. Government/semi-industrial grants (e.g. for metrology research) can support tech development.

VIII. Assistant's Role Statement

As an industry research and market-intelligence assistant, I compile and synthesize up-to-date information from industry reports, technical sources, and market analyses to provide comprehensive, cited insights. My role is to act as a knowledgeable partner, presenting a structured overview of technical processes, market trends, and competitive landscape tailored to your strategic needs, with references to authoritative sources for validation.

7.2 Gemini ('Deep Research' mode) - Summarized

The original response was summarized, also by Gemini, because it was quite detailed and therewith relatively long. To be used as a benchmark, it is desired to have a shorter version of it. If the reader is interested in the original Gemini Deep Research Market Analysis Report, the PDF version of it can be forwarded.

I)

1. Semiconductor Manufacturing Process Steps:

- Front End of Line (FEOL):
- Wafer Selection, CMP, Cleaning
- Shallow Trench Isolation (STI) / LOCOS
- Well Formation
- Gate Module Formation
- Source and Drain Module Formation
- Surface Treatment for Contacts
- Back End of Line (BEOL): 7. Metallization (Interconnect Deposition) 8. Photoresist Application, Exposure, Etching 9. Via Formation
- Post-Fabrication (Post-Fab): 10. Wafer Testing 11. Die Separation 12. IC Packaging 13. Final Device Testing

2. X-ray Applications in Semiconductor Manufacturing:

2.a) Current X-ray Applications:

- **Wafer Inspection:** Detects defects (particles, scratches, pattern deviations) and monitors contamination.
- **Package Inspection:** Ensures integrity of encapsulation and solder joints, detects voids, cracks, wire bond defects in packaged devices, especially for advanced packaging and 3D ICs (TSVs, bonding layers).
- **Failure Analysis (FA):** Examines internal structure of failed devices to pinpoint root causes.

- Metrology: Characterizes materials (thin film thickness, composition, roughness, density, porosity, crystal structure defects) using techniques like TXRF, WDXRF, EDXRF, XRR, HRXRD, CDSAXS, XRD, XRT.
- Circuit Debugging: Enables microns-scale probing of intact devices.
- Often combines 2D (faster, cost-effective for simple inspections) and 3D CT (for detailed internal analysis, isolating layers).

2.b) Future X-ray Applications:

- AI and Machine Learning (ML) Integration: For automated defect classification, improved process control, spectral unmixing, synthetic defect generation (GANs), and Explainable AI (XAI).
- Miniaturization and 3D Design: Continued demand for high-resolution imaging and multiple inspection techniques for smaller structures, chiplet integration, and advanced packaging.
- Advanced X-ray Sources: Focus on Sealed Transmissive Tubes with crystal filament technology for higher power, resolution, and lifetime.
- Increased Demand for 3D X-ray Systems: Fastest-growing segment due to complexity of 3D structures.
- Zero-Defect Strategy: Drives early, in-line inspection to reduce escalating defect costs.

II)

1. X-ray Source, Tube, and Generator Suppliers to Semiconductor Manufacturers (System Integrators):

1. Rigaku Corporation
2. Bruker Corporation
3. Nordson Corporation
4. Comet Yxlon GmbH
5. Carl Zeiss AG
6. SEC Co.,Ltd
7. Shenzhen Unicomp Technology Co., Ltd
8. Sigray, Inc
9. Other manufacturers of Wafer X-Ray Inspection Machines: ASML Veldhoven, Component Technology Pte Ltd, Dukin Co., Ltd, Guangdong Zhengye Technology Co., Ltd, Mars Tohken Solution, Shenzhen Wellman X-Ray Solution Co., Ltd, Shenzhen Wisdomshow Technology Co.,ltd .

2. X-ray Source, Tube, and Generator Suppliers to OEMs:

- Oxford Instruments (explicitly offers standalone components like Microfocus X-ray Sources, Glass Envelope X-ray Tubes, Potted X-ray Tubes, and X-ray Tube Power Supplies) .
- Rigaku Corporation (sells standalone X-ray sources, tubes, or generators as part of its components product line) .
- Sigray, Inc (supplies standalone X-ray sources like "Multi-Target X-ray Source" and "Talbot-Lau X-ray Source").

- Shenzhen Unicomp Technology Co., Ltd (developed China's first closed hot cathode micro-focus X-ray source, indicating potential for OEM supply) .
- SEC Co.,Ltd (has localized X-ray generators, implying component production) .
- 3. Top 5 Largest Semiconductor Manufacturers (by 2025 Brand Value):
- NVIDIA (\$87.9 billion)
- TSMC (\$34.2 billion)
- Intel (\$14.3 billion)
- SK hynix (\$13.7 billion)
- Broadcom (\$11.6 billion)

III)

1. Non-X-ray Inspection Technologies and Their Applications:

- Optical Metrology/Microscopy: Detects surface anomalies (particles, scratches, pattern defects) using visible/UV light; used for darkfield wafer surface inspection, mask/inline wafer inspection, layer thickness (ellipsometry), cross-section analysis .
- Electron Microscopy (SEM/TEM): Uses electron beams for high-resolution imaging; SEM for surface analysis, defect detection, CD control; TEM for atomic-level internal structure.
- Atomic Force Microscopy (AFM): Scans surface with fine tip for nanoscale surface characterization (topography, roughness, step heights).
- Infrared (IR) Microscopy/Imaging: Detects defects in IR-transparent materials like silicon (cracks, delamination, voids, stress fractures); used for solar ingot inspection, thermal inspection .
- Ultrasonic Imaging: Uses high-frequency sound waves to characterize materials, useful for thick/opaque materials.
- Ellipsometry: Measures thin-film thickness, uniformity, and optical properties using polarized light.
- Overlay Metrology: Ensures sub-nanometer alignment of lithographic layers.

2. Disadvantages of Current Non-X-ray Methods and Why Not X-ray?

- Optical Metrology/Microscopy: Cannot see through opaque materials without destructive cross-sectioning. X-ray is preferred for internal/subsurface defects.
- Electron Microscopy (SEM/TEM): Slower, more expensive, requires extensive sample preparation (not inline), TEM is destructive. E-beam equipment is very costly (around \$10M USD) and cannot detect all defects. X-ray is preferred for non-destructive, faster internal 3D views.
- Atomic Force Microscopy (AFM): Slow, contact-based (risk of damage), limited scan areas (not suitable for whole-wafer inspection). X-ray is preferred for internal structures and faster large-area scans.
- Infrared (IR) Microscopy/Imaging: May struggle with defects not involving significant density changes. X-ray can detect density differences.
- Ultrasonic Imaging: Lower resolution than optical, requires immersion (contamination risks, handling challenges). X-ray is preferred for non-contact, higher resolution internal imaging.
- Destructive Techniques: Expensive, time-consuming, not viable for inline/high-throughput, sample loss, risk missing defects due to limited sample sizes .

3. Advantages of Using X-rays Instead:

- **Non-Destructive Internal Inspection:** Penetrates opaque materials (silicon) to reveal internal defects (voids, cracks, delaminations, wire bond integrity) without damage .
- **High Resolution for Complex Structures:** Effective for advanced packaging and 3D ICs; CT allows isolation of individual layers, increasing defect detection likelihood in complex devices.
- **Material Density and Composition Sensitivity:** Detects internal defects based on density/composition differences. XRF determines elemental composition. XRD assesses crystal structures, material stresses.
- **Versatility Across Manufacturing Stages:** Applications from wafer inspection to final package inspection and failure analysis .
- **Complementary to Other Methods:** Fills gaps where other methods are weak (e.g., internal defects vs. delamination for acoustic).

IV)

1. X-ray Lithography (XRL): Opportunities:

- Enables patterning of extremely small feature sizes (below 1 nm) by overcoming optical diffraction limits.
- Potential for integrated circuit manufacturing at 130 nm and below.
- Projected robust market growth (8.5% CAGR, exceeding \$6.5 billion by 2033) driven by miniaturization, high-performance computing, MEMS, and biomedical devices.
- 5 nm - 8 nm application segment expected to dominate.

Requirements:

- Synchrotron sources preferred for output and reliability.
- Improved performance for preproduction aligners to meet error budgets at 130 nm and below.
- Specific X-ray absorber materials on X-ray transparent membranes for masks.
- Accurate adjustments (parallelism, small gaps) without mask damage.

Challenges (Technical and Economical):

- **Economical:** Prohibitively high costs of materials (e.g., gold for masks). High capital expenditure for equipment.
- **Technical:** Mask fabrication is most difficult (defect-free masks, image placement, CD control, yield). Controlling stresses and ensuring mask stability (radiation damage). Need for improved e-beam mask writers. Accurate correction for magnification errors and extendibility to 70 nm ground rules.
- **Other:** Stringent safety regulations, complex technology requiring specialized expertise, competition from alternative lithography.

2. X-ray Diffraction (XRD): Opportunities:

- Measures critical parameters: crystal structure, lattice constants, alloy concentrations, strain, film thicknesses, interdiffusion.
- Crucial for nanometrology, technology scaling, and product innovation.
- Applications in compound semiconductors, memory, MEMS, power devices, advanced packaging.

- Used for unpatterned epitaxial films (HRXRD) and crystal orientation of wafers/ingots (XRD).

Requirements:

- Precise equipment: high-energy X-ray source (e.g., copper block at 40 kV), monochromator (e.g., 4-crystal Germanium).
- Precise sample and detector rotation (0.001° angular resolution).
- High detector resolution (mechanical slits, additional monochromators).
- Ability to perform various scan types (ω scans, $\omega/2\theta$ scans) for reciprocal space mapping.
- Nanometer-scale resolution and repeatability .

Challenges (Technical and Economical):

- Technical: Need for extreme precision and high-resolution components. Complexity in setup and operation requires specialized expertise. Maintaining high-quality, stable X-ray sources and detectors.
- Economical: High capital investment due to specialized nature.

3. X-ray Fluorescence (XRF): Opportunities:

- Determines elemental composition of materials non-destructively.
- Essential for analyzing advanced semiconductor materials and multi-layer chip designs.
- Measures thin film thickness and composition.
- TXRF valuable for wafer surface contamination metrology (trace elements like Na, Mg, Al, transition metals, heavy elements).
- Used for bump composition, under bump metallization, trace residue, and dopant monitoring in FEOL processes.
- Fast characterization tool for material chemistry specifications.

Requirements:

- Primary X-ray source with sufficient energy.
- Detector system to measure emitted fluorescent X-rays.
- High sensitivity, especially for light elements.
- Vapor-Phase Decomposition (VPD) capability for lowest detection limits in TXRF.

Challenges (Technical and Economical):

- Technical: Low fluorescence yield for light elements limits sensitivity. VPD drying process can be difficult and requires automated equipment or controlled environment . VPD TXRF can lose spatial information; heavy elements are harder to recover in VPD .
- Economical: High precision equipment implies significant cost.
- Safety: Strict adherence to ALARA (As Low As Reasonably Achievable) principle for radiation safety; requires training, never aiming at people, never holding samples.

V) Broader Market Dynamics and Technological Shifts:

- Advanced Packaging and 3D Integration: Drives demand for high-resolution X-ray systems to inspect complex internal structures, chiplet integration.
- Miniaturization and Advanced Nodes: Continuous shrinking of feature sizes (e.g., below 5 nm) increases demand for sophisticated X-ray inspection and lithography.
- Emergence of New Semiconductor Materials: Introduction of SiC, GaN, GaAs, InP, Ga₂O₃ increases demand for metrology capable of characterizing these new substrates (e.g., XRT).
- AI and Machine Learning Integration: Leveraged for automated defect classification, improved process control, and enhanced inspection speed/accuracy; AI chip production increases metrology demand.
- Industry 4.0 and Automation: Drives demand for operator-free, automated X-ray systems and integration with AGVs to improve factory throughput.
- Zero-Defect Strategy and Yield Optimization: Escalating costs of late-stage defects incentivize early, in-line inspection and precise metrology.
- Geopolitical Factors and Supply Chain Resilience: Concerns like FOCI risk, regulations on foreign investments, geographic concentration, and cybersecurity threats impact supply chains, necessitating holistic risk assessment.
- Sustainability and Energy Efficiency: Growing emphasis on energy audits, renewable energy, and closed-loop systems within the industry .
- Market Concentration: Moderate to high concentration in X-ray inspection systems market.

VI)

1. Market Trends and Potential of X-ray Inspection: Market Growth Projections:

- Global semiconductor manufacturing X-ray measurement and inspection equipment: \$587M (2025) to 6.0% CAGR (2025-2033) .
- Global X-ray inspection systems (electronics/semiconductors): \$2.5B (2025) to >\$4.5B (2033) at 8% CAGR .
- Semiconductor Metrology Equipment Market: \$7.5B (2024) to \$13.4B (2032) at 7.5% CAGR (2026-2032).
- Semiconductor Metrology and Inspection Market: \$9.8B (2024) to \$18.7B (2034) at 6.9% CAGR.
- X-ray Lithography Equipment Market: \$3.274B (2025) to >\$6.5B (2033) at 8.5% CAGR.

Key Growth Drivers:

- Increasing demand for advanced semiconductor devices.
- Rising complexity of semiconductor fabrication.
- Demand for higher-quality, miniaturized, complex electronic components.
- Advanced technological advancements in 3D X-ray systems.
- Burgeoning adoption of automation.
- Expansion of X-ray applications into MEMS and biomedical devices.
- Significant growth in advanced packaging technologies.
- Expansion of semiconductor manufacturing capacity.

- Emergence of new semiconductor materials (SiC, GaN).
- Substantial investments in AI chip production.
- Rising adoption of 5G and IoT.
- Increasing need for effective quality control.
- Government initiatives (e.g., CHIPS and Science Act).

Key Trends:

- Widespread adoption of 3D X-ray systems .
- Growing integration of AI and ML algorithms .
- Miniaturization driving innovation in X-ray equipment design .
- Increased integration with big data analytics .
- Development of custom-designed solutions.
- Continuous improvements in X-ray source technology and detection methods.

Regional Growth: Strongest in Asia-Pacific (China, South Korea, Taiwan, Japan); significant in North America and Europe .

2. Hurdles to Entering the Semiconductor Market:

- High Initial Investment Costs: Substantial capital expenditure for X-ray lithography and inspection systems.
- Technological Complexity and Specialization: Requires high resolution, consistent X-ray sources, and deep technical expertise for design, operation, and maintenance .
- Rapid Technological Advancements & Obsolescence Risk: Fast pace of innovation leads to potential obsolescence.
- Stringent Quality and Reliability Requirements: "Zero defect strategy" and critical reliability for sensitive applications (aerospace, automotive, medical).
- Regulatory Compliance and Safety: Strict safety regulations (X-ray radiation, ALARA principle) and complex international compliance.
- Established Competition & Market Concentration: Market dominated by a few major players; niche monopolies exist (e.g., KLA in E-beam).
- Supply Chain and Geopolitical Risks: FOCI risk, foreign investment restrictions, geographic concentration, natural disasters, cybersecurity threats.
- Customer Relationships and Qualification: Long qualification cycles and need for custom solutions.

VII)

1. Market Sizing and Growth Projections: Overall semiconductor market: 15% CAGR (2024-2032).

X-ray related equipment markets show robust growth:

- Semiconductor manufacturing X-ray measurement and inspection equipment: 6.0% CAGR (2025-2033).
- X-ray inspection systems (electronics/semiconductors): 8% CAGR (2025-2033).

- Semiconductor Metrology Equipment Market: 7.5% CAGR (2026-2032).
- Semiconductor Metrology and Inspection Market: 6.9% CAGR (to 2034).
- X-ray Lithography Equipment Market: 8.5% CAGR (2025-2033).

Growth driven by miniaturization, advanced packaging, 3D integration, and AI/ML demand.
Strongest regional growth in Asia-Pacific; significant in North America and Europe.

2. Key Market Drivers and Restraints: Drivers:

- Technological Advancements (miniaturization, 3D integration, new materials).
- Demand for High-Performance Devices (consumer electronics, 5G, IoT, AI, automotive, healthcare).
- Quality Control Imperatives ("zero-defect strategy," yield optimization, reliability).
- Automation and Industry 4.0 (AI/ML integration, automated production lines).
- Government Support (e.g., CHIPS Act).

Restraints:

- High Capital Expenditure.
- Rapid Technological Obsolescence.
- Technological Complexity.
- Stringent Regulatory Environment (safety, compliance).
- Intense Competition.
- Supply Chain Vulnerabilities (geopolitical, natural disasters, cybersecurity).
- Cost of Materials (e.g., for XRL).

3. Competitive Landscape:

- System Suppliers: Rigaku, Bruker, Nordson, Comet Yxlon, Carl Zeiss, SEC Co.,Ltd, Shenzhen Unicom Technology Co., Ltd, Sigray, Inc, and others .
- Component Suppliers: Oxford Instruments, Rigaku, Sigray, and potentially SEC Co.,Ltd and Shenzhen Unicom Technology Co., Ltd (due to internal component development) .
- Characterized by a "dual-layer" market strategy (integrated systems vs. standalone components) .
- Increasing vertical integration by system integrators (e.g., SEC, Unicom developing own components).

4. Strategic Recommendations for X-ray Component Suppliers:

1. Prioritize R&D for Advanced Packaging and 3D Integration: Focus on higher resolution, faster 3D imaging, and sub-micron inspection capabilities.
2. Integrate AI/ML Readiness: Ensure hardware compatibility with AI, robust data interfaces, and explore partnerships with AI software developers.
3. Emphasize ROI and "Cost of Failure": Highlight yield improvement, enhanced reliability, and avoidance of costly failures to justify investment.

4. Adopt Dual-Layer Market Strategy with Niche Specialization: Supply cutting-edge components to OEMs and develop niche, high-value systems where core technology offers distinct advantages .
5. Leverage Regulatory Compliance as a Differentiator: Invest in safety protocols and certifications to build trust and competitive advantage.
6. Monitor Geopolitical and Supply Chain Shifts: Consider diversified manufacturing/R&D or robust supply chain risk management.
7. Explore Sustainability: Develop energy-efficient technologies and contribute to lower waste production .

VIII)

Role and Persona Statement: Industry analyst with in-depth knowledge of the semiconductor market and X-ray technology.

7.3 Perplexity ('Deep Research' mode)

I) Semiconductor Manufacturing Steps & X-ray Applications

FEOL Steps:

1. Wafer Manufacturing
2. Oxidation
3. Photolithography
4. Etching
5. Deposition/Ion Implantation
6. Transistor Formation (Gate/Source/Drain)

BEOL Steps:

- 7. Metal Wiring (Interconnects)
- 8. Packaging
- 9. Final Testing

X-ray Use: 2.a) Today:

- Packaging: Failure analysis (e.g., detecting voids, cracks)
- BEOL Interconnect Inspection: Via/metallization defects
- Circuit Debugging: X-ray Assisted Device Alteration (XADA) for backside power delivery

2.b) Future:

- Advanced Lithography: X-ray lithography (XRL) for sub-3 nm nodes
- In-line Process Monitoring: Real-time defect detection in FEOL/BEOL

II) Key Companies & Semiconductor Manufacturers

X-ray Suppliers to Semiconductor Manufacturers:

- Sigray (3D X-ray microscopes, XADA)
- Comet Yxlon (CT systems for packaging)
- Nikon Metrology
- Nordson Test & Inspection

X-ray Suppliers to OEMs:

- Hamamatsu Photonics (X-ray tubes)
- Varex Imaging (generators)
- Rigaku (sources)

Top 5 Semiconductor Manufacturers:

- TSMC
- Samsung
- Intel
- SK Hynix
- Broadcom

III) Competing Inspection Technologies in Semiconductor Manufacturing

FEOL (Front End of Line):

- Common inspection technologies: Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM)
- Why not X-ray? SEM/TEM offer extremely high resolution for surface and cross-sectional analysis but are often destructive and slow, making them less suitable for high-throughput or non-destructive in-line inspection.
- Disadvantages of current methods: Destructive sample preparation, time-consuming, limited to small sample areas.
- Advantages of X-ray: Non-destructive, allows for bulk and 3D internal analysis, can inspect buried structures without sample destruction.

Photolithography:

- Common inspection technology: Optical Microscopy
- Why not X-ray? Optical microscopy is fast and cost-effective, but its resolution is limited by the wavelength of light, especially below 10 nm feature sizes.
- Disadvantages of current methods: Insufficient resolution for advanced nodes, cannot resolve smallest features.
- Advantages of X-ray: Higher (sub-nanometer) resolution possible, can penetrate layers to inspect features below the surface.

BEOL (Back End of Line):

- Common inspection technology: Electrical Testing (e.g., probing, IV measurements)
- Why not X-ray? Electrical testing is fast and directly measures circuit function but is limited to detecting only surface or functional defects, not internal structural issues.
- Disadvantages of current methods: Cannot detect hidden or internal defects, no spatial information about defect location.
- Advantages of X-ray: Can detect internal and 3D defects in interconnects and vias, provides spatially resolved defect information.

Packaging:

- Common inspection technology: Acoustic Microscopy (Scanning Acoustic Microscopy, SAM)
- Why not X-ray? Acoustic microscopy is good for detecting delamination and some voids but has limited resolution for dense, complex interconnects.
- Disadvantages of current methods: Poor resolution for fine features, limited penetration in dense materials.
- Advantages of X-ray: High-resolution imaging of voids, cracks, and defects in dense and multi-layered packages, non-destructive and fast for in-line inspection.

IV) X-ray Techniques in Semiconductors**X-ray Lithography (XRL):**

- Opportunities: Enables sub-3 nm patterning
- Challenges: Requires synchrotron-grade sources (costly), mask alignment complexity.

X-ray Diffraction (XRD):

- Use: Crystal structure/stress analysis in FEOL
- Requirements: High-intensity sources (e.g., rotating anodes).

X-ray Fluorescence (XRF):

- Use: Contamination analysis (e.g., metals on wafers)
- Challenges: Limited sensitivity for light elements.

V) Additional Opportunities

- 3D Packaging: Multi-chip module inspection
- Advanced Nodes: In-line metrology for EUV lithography.
- Backside Power Delivery: XADA for fault isolation
- Materials R&D: XRD/XRF for novel dielectrics/metals

VI) Trends & Market Hurdles**Trends:**

- 20-30% CAGR for X-ray inspection due to advanced packaging
- Shift toward in-line process control (vs. post-fab QA).

Hurdles:

- High cost of X-ray systems vs. optical/electrical methods.
- Integration with fab workflows (throughput constraints).
- Competition from E-beam inspection.

VII) Semiconductor Market Analysis

Market Size: \$600B (2025), driven by AI/5G/IoT

- Key Drivers:
- Miniaturization (Moore's Law) → Demand for high-resolution inspection
- Heterogeneous Integration → 3D packaging requires X-ray CT

X-ray Segment: \$1.2B (2025), dominated by failure analysis

VIII) Assistant Role

I am an AI trained in semiconductor manufacturing and market analysis, synthesizing data from industry publications (e.g., SEMI, Sigray) and technical sources to provide actionable insights for X-ray equipment vendors.

8 ANNEX C - LLM-generated benchmark

- "aggregation model": "gemma3:27b-it-q4_K_M"
- "aggregation temperature": 0.1
- References: 1. ChatGPT "Deep Research", 2. Gemini "Deep Research", 3. Perplexity "Deep Research"

8.1 User Prompt 1)

1. Name all the steps in semiconductor manufacturing, numbered, and state whether they are the "Back End of Line" (BEOL) or the "Front End of Line" (FEOL). 2: In which of these steps are X-rays used and why - 2.a) today and 2.b) possibly in the future

Aggregation: The aggregated answer combines the detailed steps from all three references, prioritizing a clear FEOL/BEOL distinction. The preparatory wafer stage is included as a preface to FEOL. The steps are numbered and categorized as FEOL, BEOL, or Post-Fabrication. The X-ray application section synthesizes the current uses (wafer/package inspection, failure analysis, metrology) and future possibilities (X-ray lithography, in-line monitoring, advanced packaging inspection) described in all references, emphasizing the benefits of X-ray imaging for subsurface features and 3D inspection. The challenges of implementing faster, higher-resolution X-ray tools are also noted. The combined list of steps is comprehensive, covering wafer preparation through final testing, and the X-ray discussion provides a nuanced view of both current and potential future applications.

1. **Wafer Preparation** (pre-FEOL): Crystal growth, wafer slicing, polishing, and cleaning.
2. **Oxidation / Thin-Film Deposition** (FEOL): Grow or deposit thin dielectric films (SiO₂, nitrides).
3. **Lithography** (FEOL): Coat with photoresist and use optical/EUV lithography to pattern features.
4. **Etching** (FEOL): Remove material (dry/wet etch) to create trenches, wells, and gate structures.
5. **Ion Implantation / Doping** (FEOL): Implant dopant ions and anneal to form source/drain and well regions.
6. **Gate Formation** (FEOL): Deposit and pattern gate dielectric and gate electrode.
7. **Silicidation** (FEOL/BEOL interface): Form silicide contacts on source/drain and gate.
8. **Inter-layer Dielectric Deposition** (BEOL): Deposit dielectric layers (PMD/ILD) and perform CMP planarization.
9. **Contact/Via Formation** (BEOL): Etch holes in dielectric to form contacts and vias.
10. **Metal Deposition and Patterning** (BEOL): Deposit metal (Al, Cu) and pattern interconnect layers.
11. **Passivation** (BEOL): Add top dielectric/passivation layer and open bond pad windows.
12. **Wafer Test** (Post-Fab): Probe electrical functionality of individual chips.
13. **Dicing** (Post-Fab): Saw or dice wafer into individual die.
14. **Packaging** (Post-Fab): Attach die to substrate, wire-bond or flip-chip, mold/cap.
15. **Final Test** (Post-Package): Electrical/thermal testing of packaged ICs.

X-ray Usage \u2013 Current (2.a) and Future (2.b):

Current: X-ray inspection/metrology is used in back-end and analysis steps. Applications include: package inspection (void/crack detection), BEOL interconnect inspection (via/metallization defects), circuit debugging (XADA), failure analysis, thin-film characterization (XRF/TXRF/XRR), and wafer crystal orientation/strain measurement (XRD).

Future: Potential applications include: X-ray lithography (XRL) for sub-3nm nodes, in-line process monitoring (FEOL/BEOL), advanced packaging inspection (3D CT), real-time film thickness control (X-ray reflectometry), and CD metrology (SAXS/X-ray scatterometry). The key benefit is the ability to image subsurface features non-destructively and probe dense materials. Challenges include developing sufficiently fast, high-resolution X-ray tools for fab integration.

8.2 User Prompt 2)

Which companies supply the semiconductor manufacturers with X-ray sources, X-ray tubes and X-ray generators, and which companies supply the OEMs active in the semiconductor market with X-ray sources, X-ray tubes and X-ray generators? Which are the 5 largest semiconductor manufacturers?

Aggregation: Combining the three responses, the aggregated answer lists the following companies as suppliers of X-ray sources, tubes, and generators to semiconductor manufacturers and OEMs: Hamamatsu Photonics, Varex Imaging, Oxford Instruments, Rigaku, Sigray, Comet Yxlon, Nordson, Moxtek, Spellman, Gulmay, Excillum, Delta Electronics, Matsusada Precision, Bruker, Carl Zeiss, SEC Co., Ltd, Shenzhen Unicomp Technology Co., Ltd, and Nikon Metrology. The top 5 semiconductor manufacturers are consistently identified as TSMC, Samsung, Intel, SK Hynix, and Broadcom (though one source lists Micron instead of Broadcom, the latter appears more consistently in recent rankings). The aggregated response prioritizes a comprehensive list of suppliers and the most frequently cited top manufacturers.

8.3 User Prompt 3)

Which inspection technologies other than X-ray are used in which steps of semiconductor manufacturing? For each of these processes: Why not X-ray? What are the disadvantages of the current non-X-ray method and what would be the advantages of using X-rays instead?

Aggregation: The aggregated answer synthesizes information from all three references, prioritizing a process-oriented breakdown of semiconductor manufacturing steps (FEOL, BEOL, Packaging) and detailing alternative inspection technologies used in each. It explains **why** X-ray isn't currently used (resolution limits, cost, speed, sample preparation, or existing effective methods), the **disadvantages** of the current non-X-ray methods (limited resolution, destructive nature, inability to see internal defects, etc.), and the **advantages** of using X-rays (non-destructive internal inspection, high resolution for complex structures, material sensitivity, versatility, and complementary nature). The aggregation emphasizes the benefits of X-ray for detecting internal defects, particularly in advanced packaging and 3D ICs, and highlights its potential to complement existing inspection techniques. The response is structured to provide a comprehensive overview of the topic, addressing all aspects of the original question.

****FEOL (Front End of Line):****

*** **Alternative Technologies:**** Optical Microscopy, Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Ellipsometry, Reflectometry, Ellipsometric Scatterometry, Profilometry.

*** **Why Not X-ray:**** Resolution limitations for fine features, slower speeds, and the effectiveness of existing optical and electron microscopy techniques.

*** **Disadvantages of Current Methods:**** Limited resolution, destructive sample preparation (TEM), time-consuming, inability to see buried layers.

*** **Advantages of X-ray:**** Non-destructive internal inspection, high resolution for complex structures, ability to measure layer thickness and uniformity, potential for 3D etch profile analysis.

****BEOL (Back End of Line):****
*** **Alternative Technologies:**** Optical CD-SEM, Scatterometry, Atomic Force Microscopy (AFM), Probe-based capacitance (PDA), Electrical Testing.

*** **Why Not X-ray:**** Cost, existing effective methods, low X-ray contrast between materials.

*** **Disadvantages of Current Methods:**** Line-of-sight limitations, destructive sample preparation (FIB/TEM), difficulty inspecting complex 3D interconnects.

*** **Advantages of X-ray:**** Non-destructive 3D visualization of multilevel interconnects and TSVs, X-ray scatterometry for non-destructive measurement of periodic features.

****Packaging:****

*** **Alternative Technologies:**** Automated Optical Inspection (AOI), Acoustic Microscopy, Shearography.

*** **Why Not X-ray:**** X-ray **is** used for solder-bump inspection and void detection, but optical and acoustic methods are also employed.

*** **Disadvantages of Current Methods:**** Inability to see internal defects without X-ray, limited penetration of acoustic methods.

* **Advantages of X-ray:** Non-destructive detection of voids, delamination, and wirebond issues, improved yield in multi-chip modules.

8.4 User Prompt 4)

Tell me more about X-ray lithography XRL, X-ray diffraction XRD and X-ray fluorescence XRF. What are the opportunities, requirements and challenges (technical and economical)?

Aggregation: This aggregation synthesizes the information from the three provided references, prioritizing comprehensive coverage of opportunities, requirements, and challenges for each technique. It aims for a balanced and detailed overview, acknowledging the varying levels of detail in the source answers.

****X-ray Lithography (XRL):****

* **Opportunities:** Enables patterning of extremely small feature sizes (below 3nm, potentially down to 1nm), overcoming optical diffraction limits. Potential applications in advanced integrated circuit manufacturing, high-performance computing, MEMS, and biomedical devices. Theoretically allows for simpler mask designs (proximity printing) compared to EUV.

* **Requirements:** Extremely bright and stable X-ray sources (often synchrotron-like or advanced plasma sources). Radiation-hard resists. Precise mask/stencil alignment.

* **Challenges:** High costs associated with X-ray sources and equipment. Mask fabrication (defect-free masks, image placement, CD control, yield). Lack of suitable resists and masks. Economic viability is doubtful given EUV adoption and high tool costs. Building a practical, high-throughput source.

****X-ray Diffraction (XRD):****

* **Opportunities:** Measures critical parameters like crystal structure, lattice constants, alloy concentrations, strain, film thicknesses, and crystal orientation. Crucial for nanometrology, technology scaling, and product innovation. Potential for in-line monitoring of epitaxial layer quality and stress.

* **Requirements:** Precise equipment including high-energy/monochromatic X-ray sources, monochromators, precise goniometers, and detectors.

* **Challenges:** Complexity in setup and operation requires specialized expertise. Maintaining high-quality, stable X-ray sources and detectors. Slow scanning and alignment. Sensitivity to small defects. Integration into fabrication lines can be difficult.

****X-ray Fluorescence (XRF):****

* **Opportunities:** Determines elemental composition of materials non-destructively. Essential for analyzing advanced semiconductor materials and multi-layer chip designs. Measures thin film thickness and composition. Valuable for wafer surface contamination metrology (trace elements). Potential for in-line sensors for real-time film monitoring.

* **Requirements:** Primary X-ray source with sufficient energy. Detector system to measure emitted fluorescent X-rays. High sensitivity, especially for light elements. Vacuum control for TXRF.

* **Challenges:** Low fluorescence yield for light elements limits sensitivity. VPD drying process can be difficult. Calibration standards are needed. Limit of detection (ppb levels require long integration).

8.5 User Prompt 5)

What else could be of interest with regard to the semiconductor market for a company that develops and sells X-ray sources, X-ray tubes and X-ray generators?

Aggregation: The three reference answers consistently highlight opportunities related to advanced semiconductor manufacturing techniques and materials. Answer 2 provides the most comprehensive overview, detailing broader market dynamics and specific applications. Answers 1 and 3 largely overlap and provide concise lists of these opportunities. Therefore, the aggregated answer will combine the detailed explanations from Answer 2 with the concise list from Answers 1 & 3 to create a thorough and easily digestible response. The aggregated answer will focus on 3D packaging/multi-chip module inspection, advanced node/EUV lithography metrology, backside

power delivery fault isolation (XADA), materials R&D utilizing XRD/XRF, and the broader trends of AI/ML integration, Industry 4.0, zero-defect strategies, geopolitical factors, and sustainability.

8.6 User Prompt 6)

What are the trends and market potential of X-ray inspection in the semiconductor market? What are the hurdles to entering the semiconductor market when offering X-ray sources, X-ray tubes and X-ray generators?

Aggregation: The semiconductor X-ray inspection market is experiencing strong growth, driven by advanced packaging, increasing device complexity, and the demand for higher quality/miniaturation. Market projections vary, but consistently show significant expansion \u2013 ranging from a 5.4% to 8.5% CAGR, reaching between \$4.5B and \$18.7B by 2032-2034. Key trends include the adoption of 3D X-ray systems, AI/ML integration, and regional growth in Asia-Pacific.

Hurdles to entry are substantial. These include high initial investment costs, technological complexity (requiring specialized expertise in high-resolution sources and systems), rapid technological advancements leading to obsolescence risk, stringent quality/reliability requirements (driven by the 'zero defect' strategy), regulatory compliance/safety concerns, established competition with entrenched players (like KLA, Zeiss, Hamamatsu, etc.), and supply chain/geopolitical risks. Long customer qualification cycles and the need for custom solutions also present challenges. Integration with existing fab workflows (throughput, cleanroom compatibility) and demonstrating a clear ROI/yield advantage are crucial for new entrants.

8.7 User Prompt 7)

Conduct a semiconductor market analysis, relevant to a company that develops and offers X-ray sources, X-ray tubes and X-ray generators, with all the steps that usually go with it.

Aggregation: The aggregated answer synthesizes information from all three sources to provide a comprehensive overview of the X-ray inspection market in semiconductors.

****Market Trends & Potential:**** The market is currently valued around \$1.2B (projected to \$1.5B by 2030) and is driven by increasing complexity in semiconductor manufacturing \u2013 specifically miniaturization, advanced packaging (like 3D integration and HBM), and the demand for high-performance chips for AI, 5G, and IoT applications. 3D X-ray (CT) imaging is the fastest-growing segment, fueled by the need for volumetric inspection of complex packages. Asia-Pacific is the leading geographic market. The push for zero-defect manufacturing and stricter reliability standards are key drivers. Digital X-ray with AI-enabled analysis is becoming increasingly important.

****Hurdles to Entry:**** New suppliers face significant barriers. These include:

1) ****Technical Qualification:**** Semiconductor OEMs have rigorous requirements for precision, cleanliness, and reliability.

2) ****Integration Challenges:**** Equipment must fit within cleanroom environments, integrate with fab automation, and ensure minimal downtime.

3) ****Capital Intensity:**** Developing X-ray systems, especially 3D CT, requires substantial R&D investment.

4) ****Competition:**** Established vendors (Zeiss, KLA, Nordson, Yxlon, Hamamatsu, Teledyne/Thermo Fisher, Comet Yxlon, etc.) have entrenched relationships.

5) ****Cost & ROI:**** Fabs assess cost-of-ownership versus yield gains, requiring new entrants to demonstrate clear ROI through yield/loss reduction studies.

6) ****Supply Chain:**** Component suppliers (Spellman, Oxford Instruments, Rigaku/NSI, Moxtek) are also competitive.

****Go-to-Market Strategies:**** Successful strategies involve partnering with established OEMs or becoming approved suppliers to foundries/OSATs. Focusing on niche segments (e.g., wirebond inspection, micro-CT) before expanding, attending industry tradeshow (SEMICON, ASMC), publishing application notes, and participating in consortia (e.g., SEMATECH) are also important. Government grants and collaborations can support technology development.

8.8 User Prompt 8)

Who are you and which role are you playing?

Aggregation: The core identity across all responses is an assistant role focused on semiconductor market analysis, specifically with expertise in X-ray technology. The responses consistently highlight data synthesis from industry publications and technical sources to provide actionable/comprehensive insights. Therefore, the aggregated answer combines these elements to present a complete picture of the persona.

9 ANNEX D - Experimental Results per User Prompt

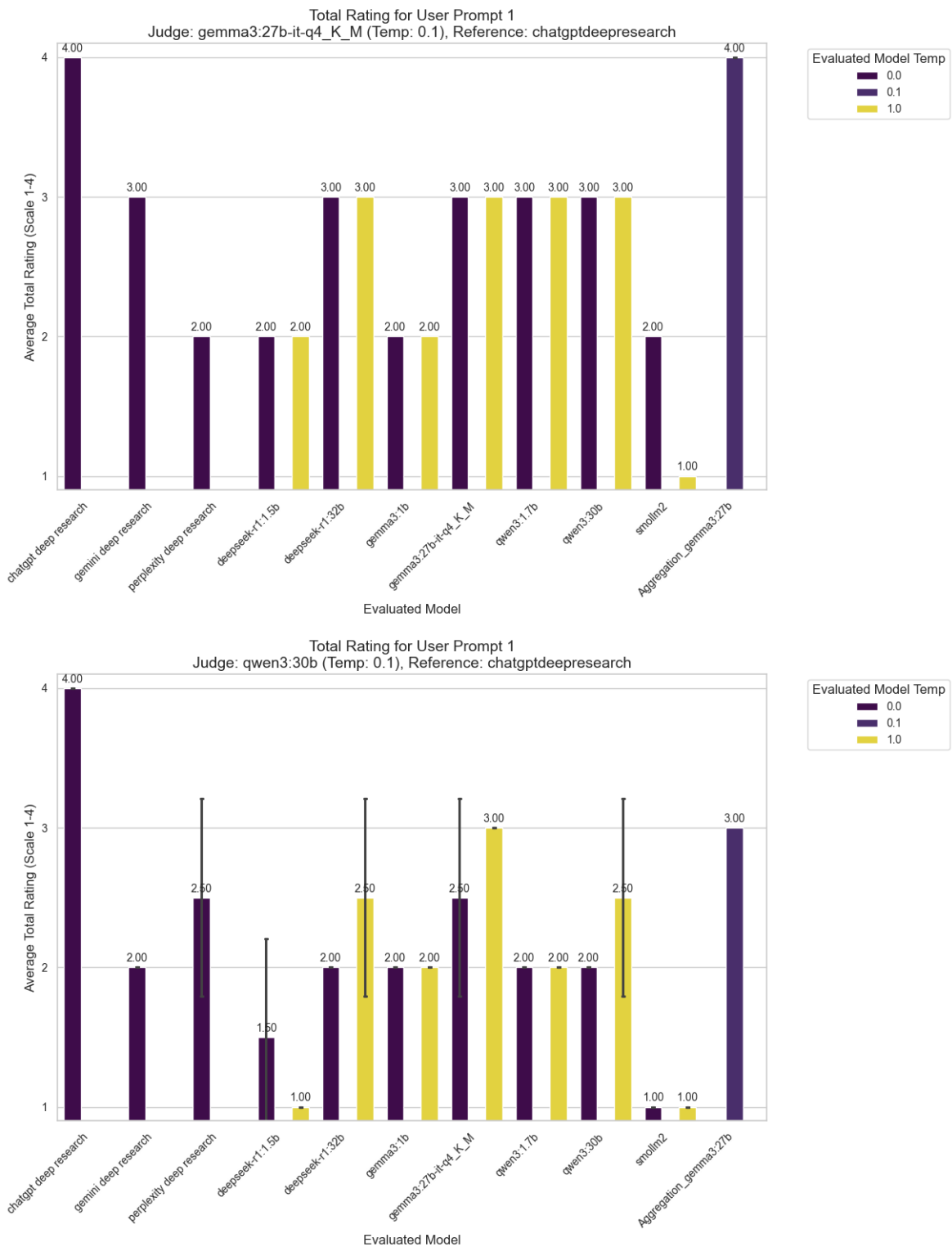


Figure 11: same style as in..., Prompt 1

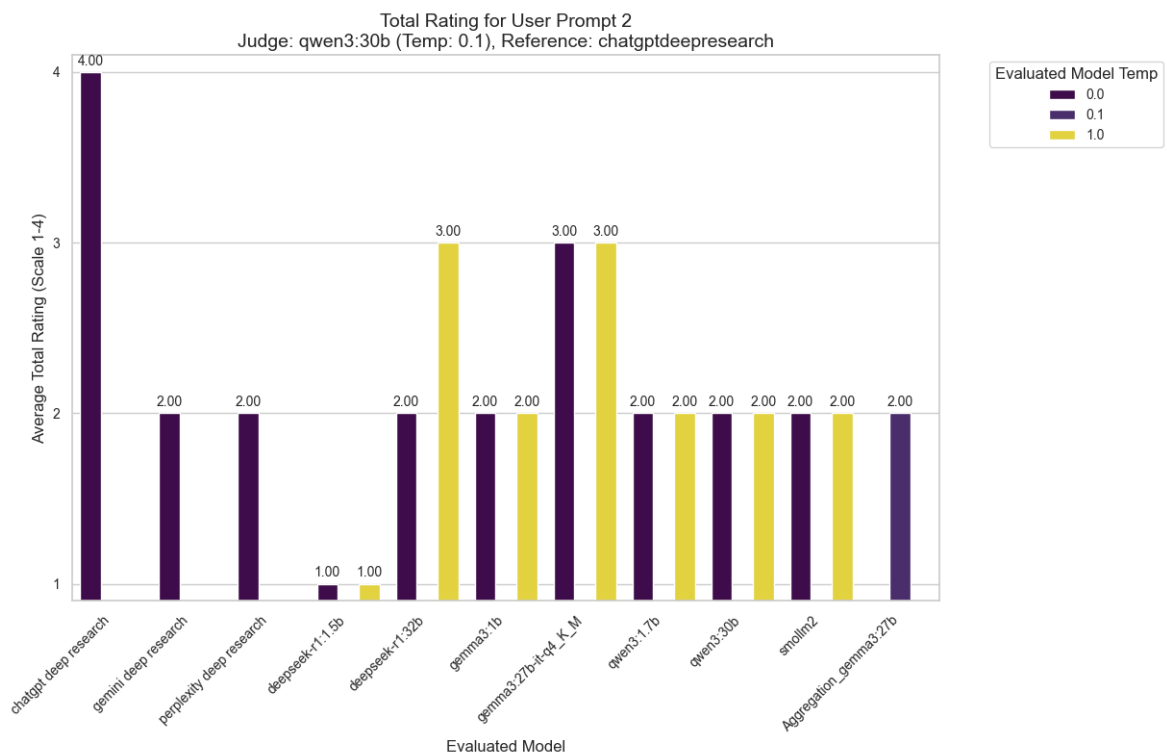
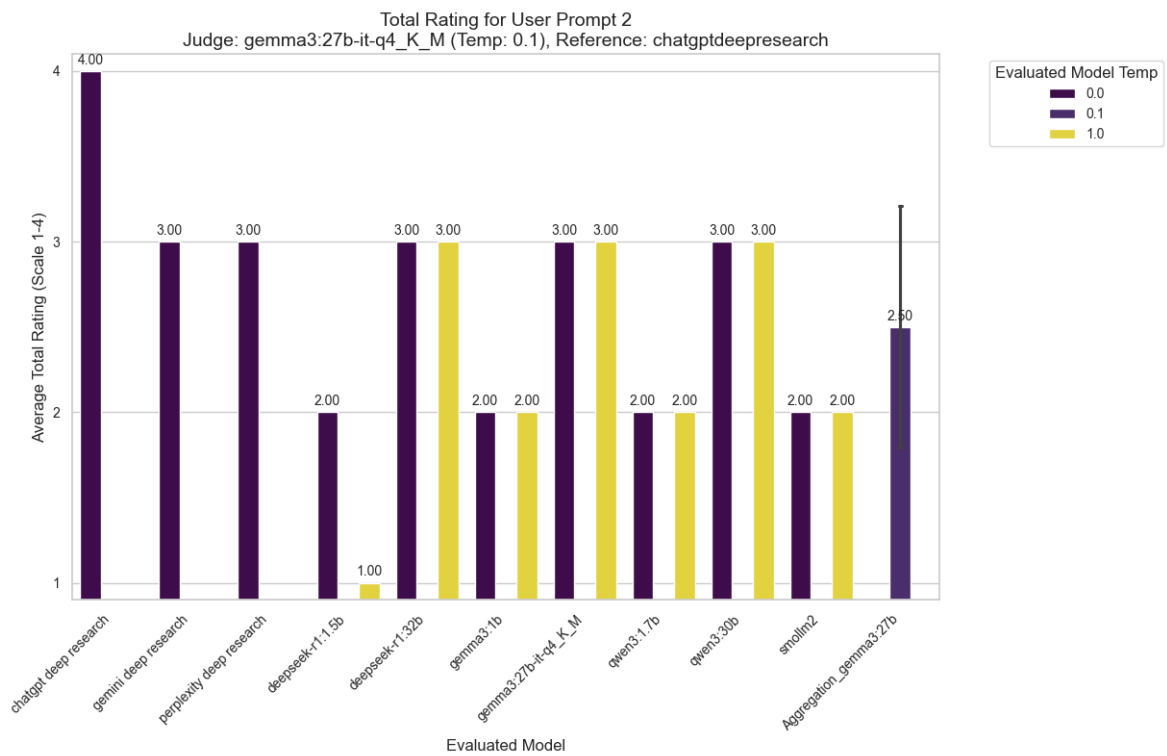


Figure 12: same style as in..., Prompt 2

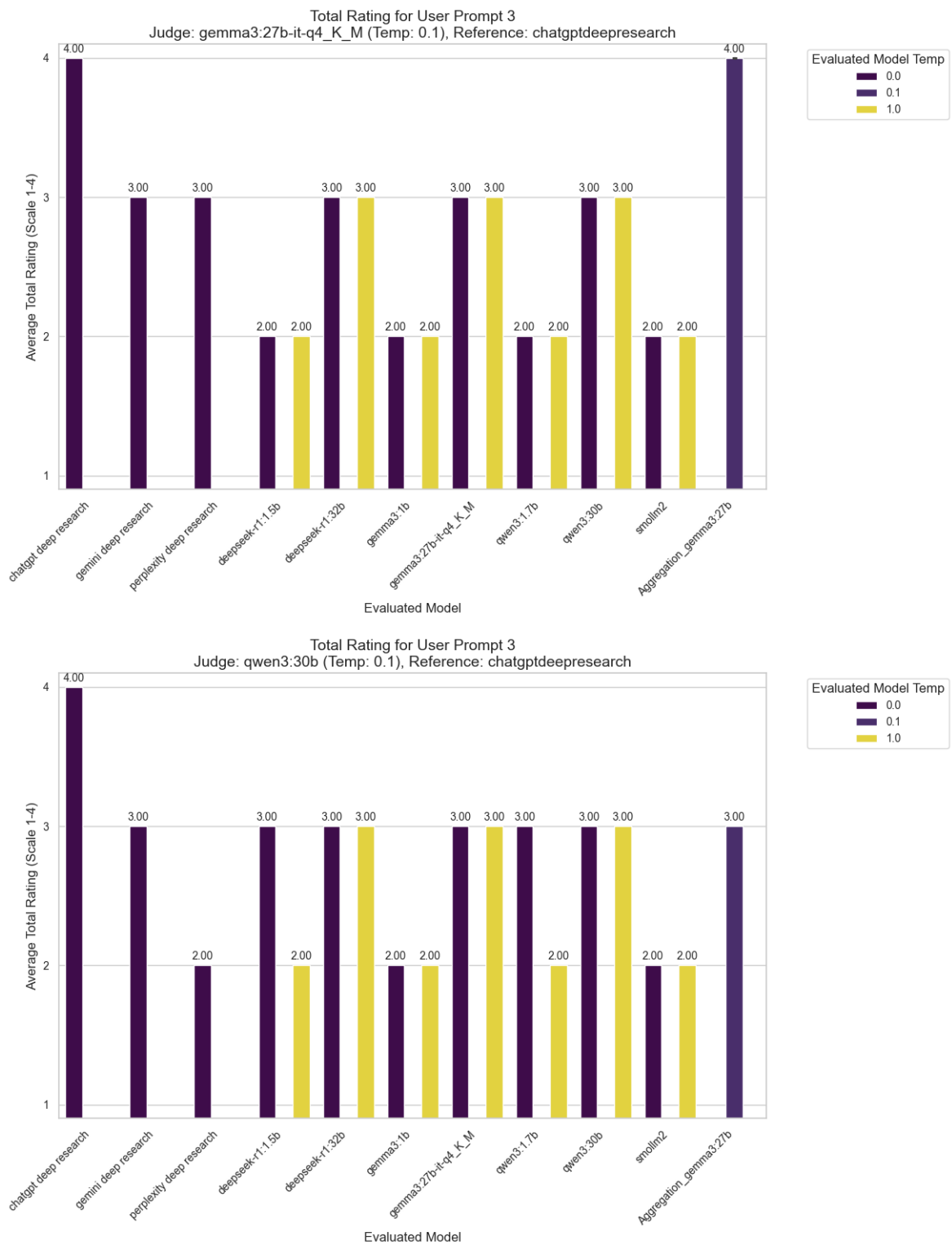


Figure 13: same style as in..., Prompt 3

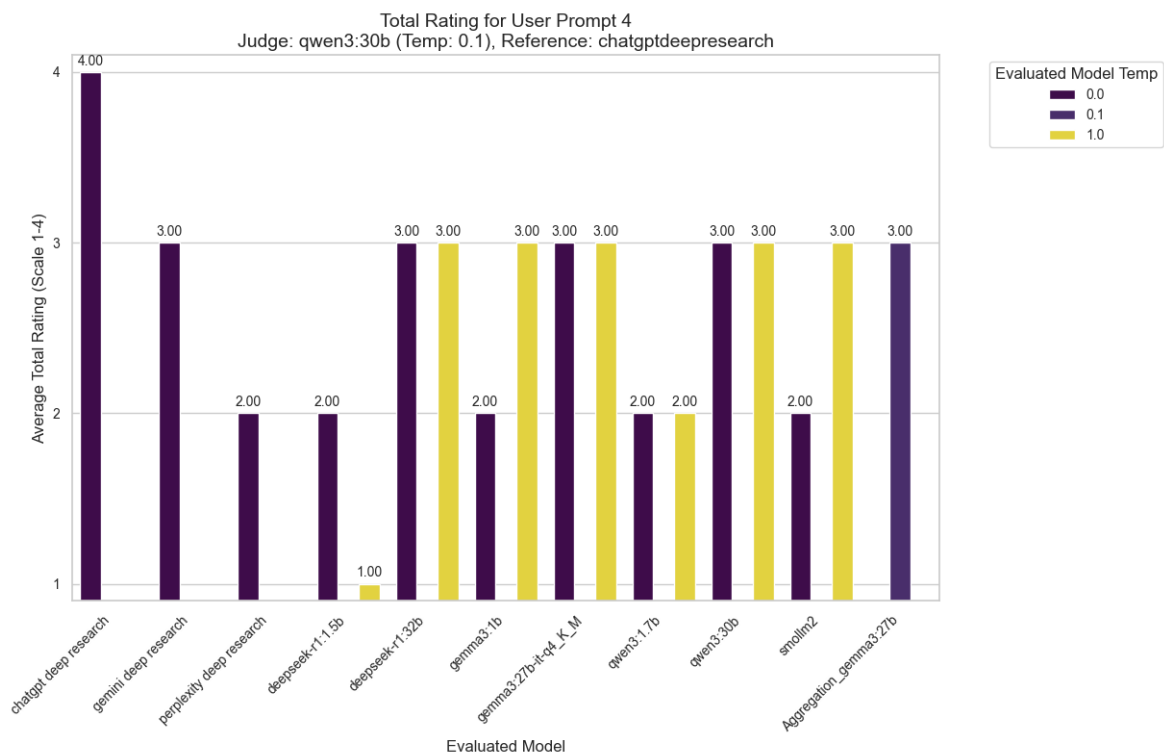
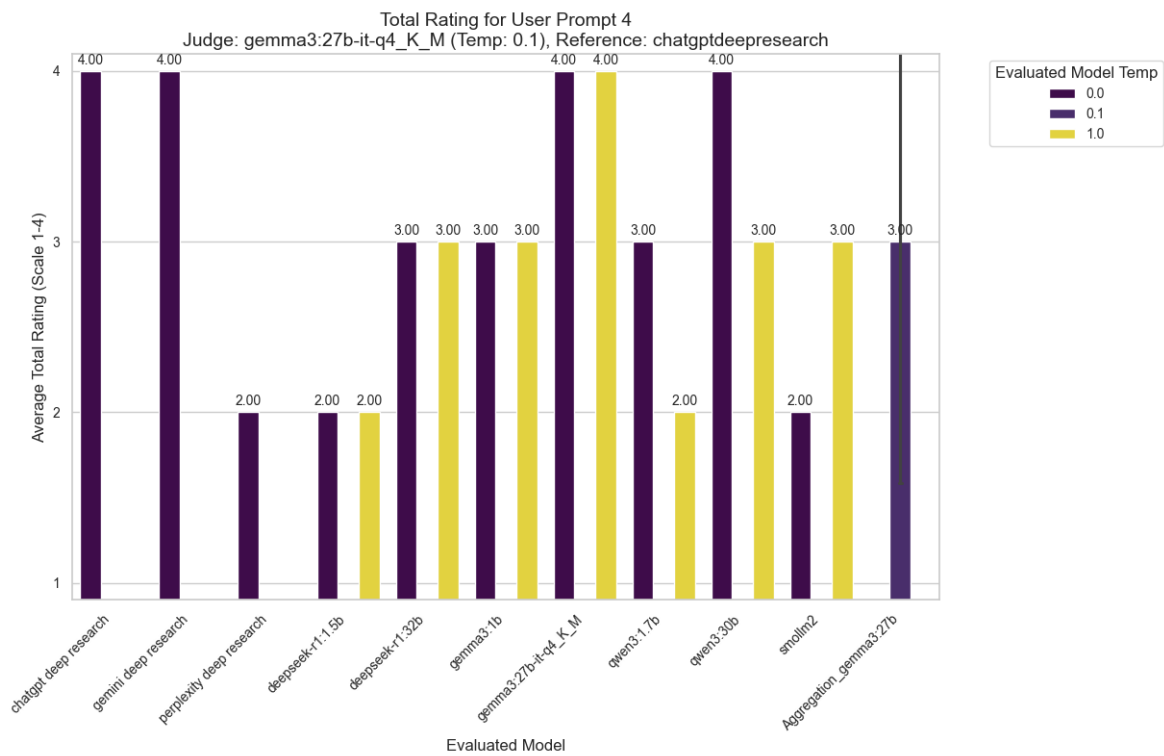


Figure 14: same style as in..., Prompt 4

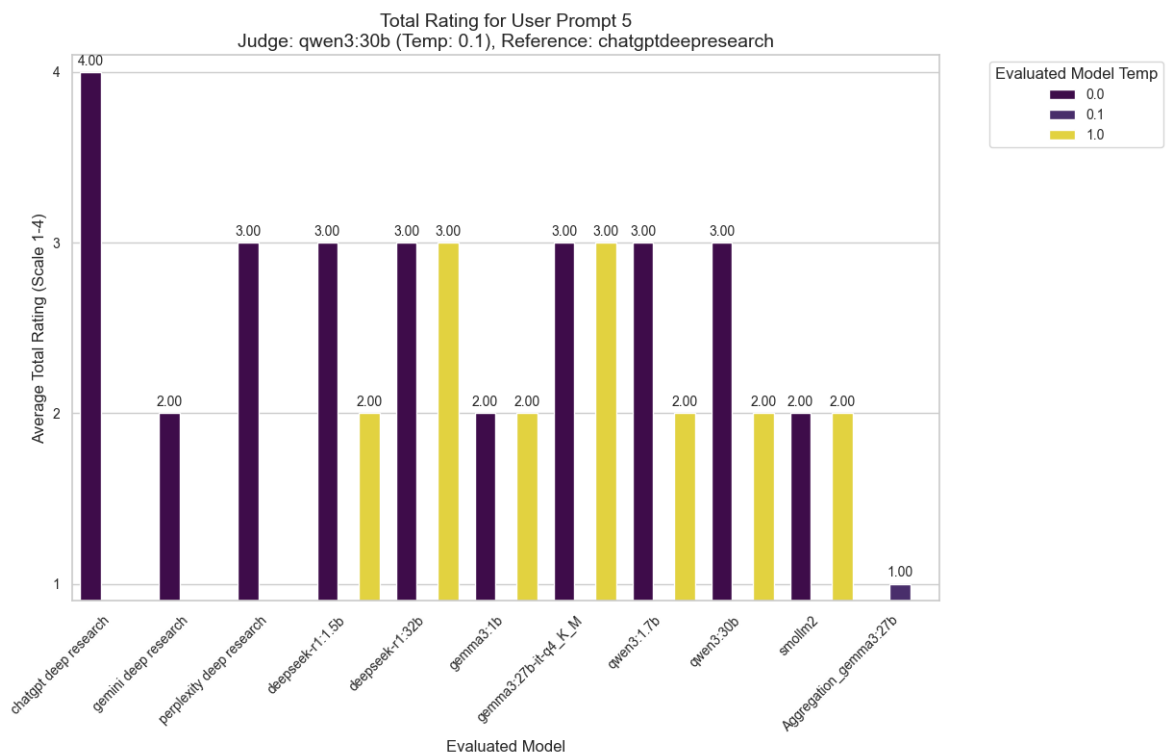
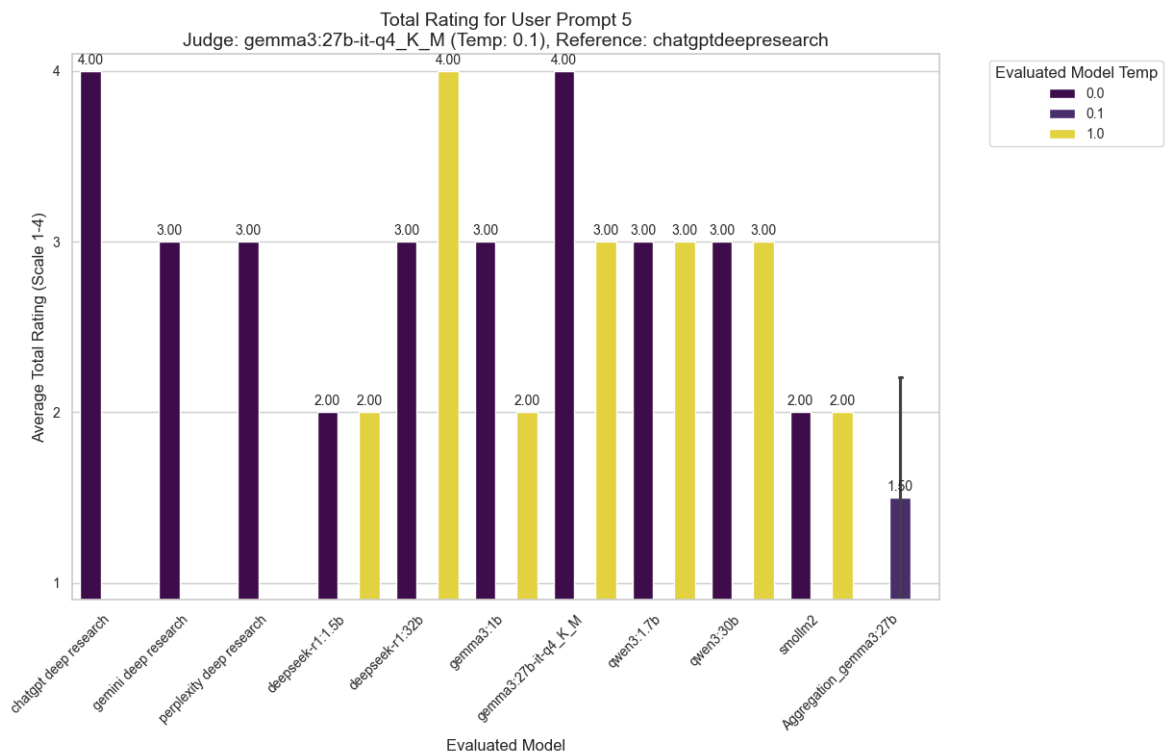


Figure 15: same style as in..., Prompt 5

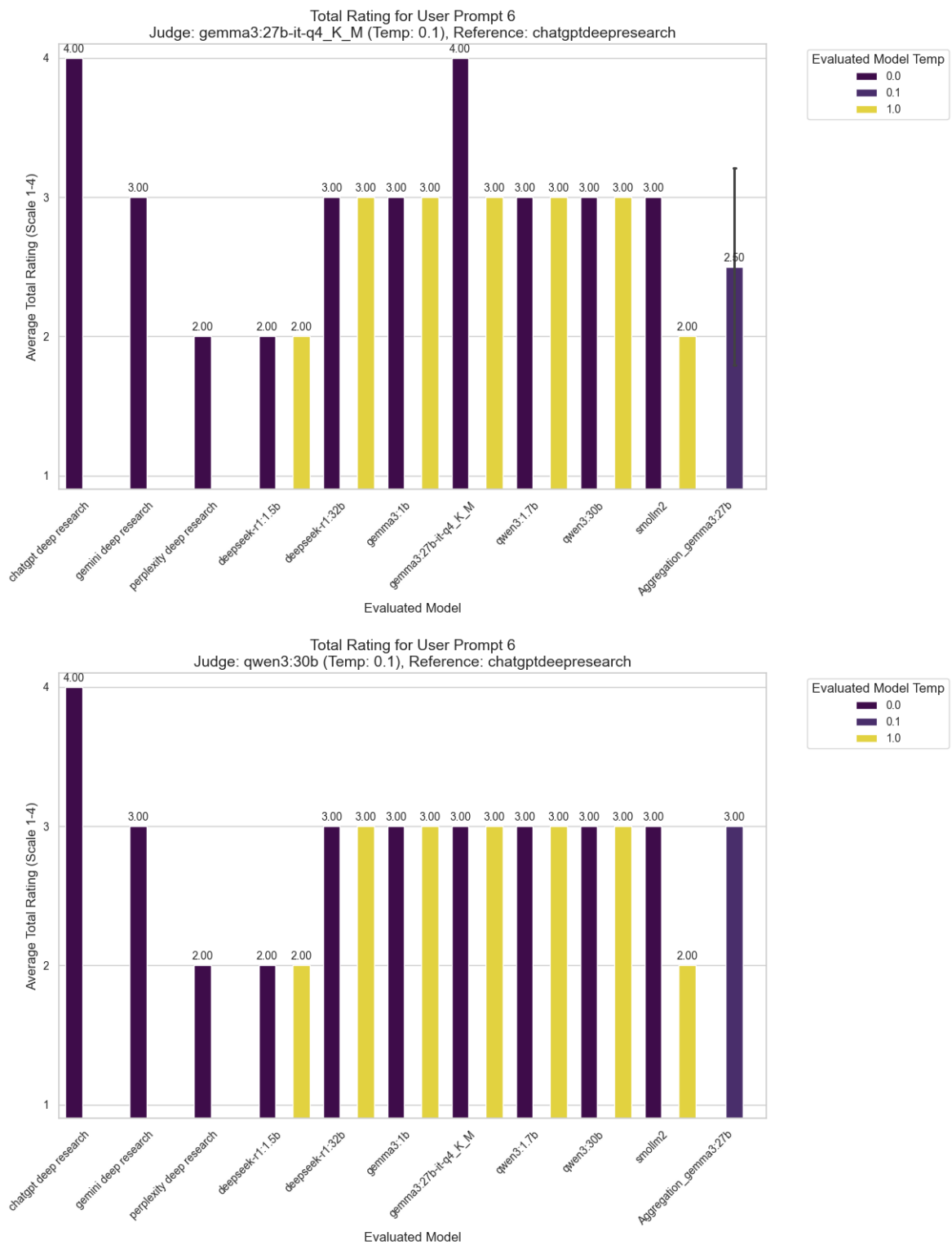


Figure 16: same style as in..., Prompt 6

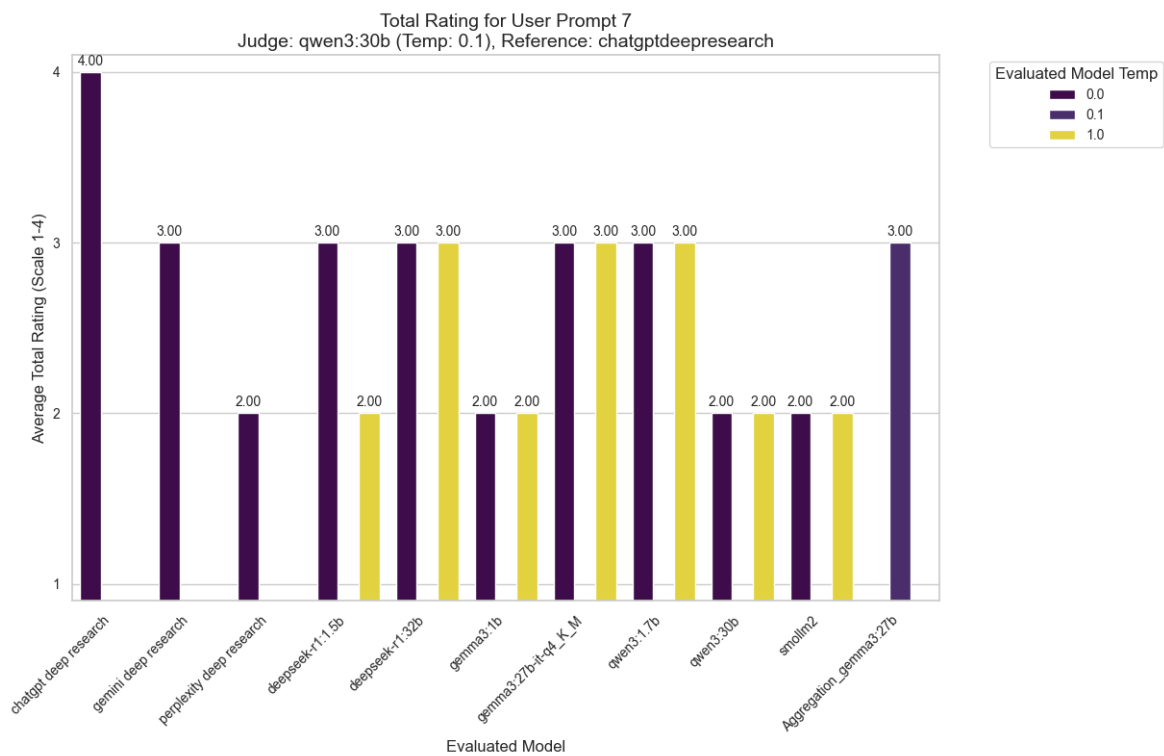
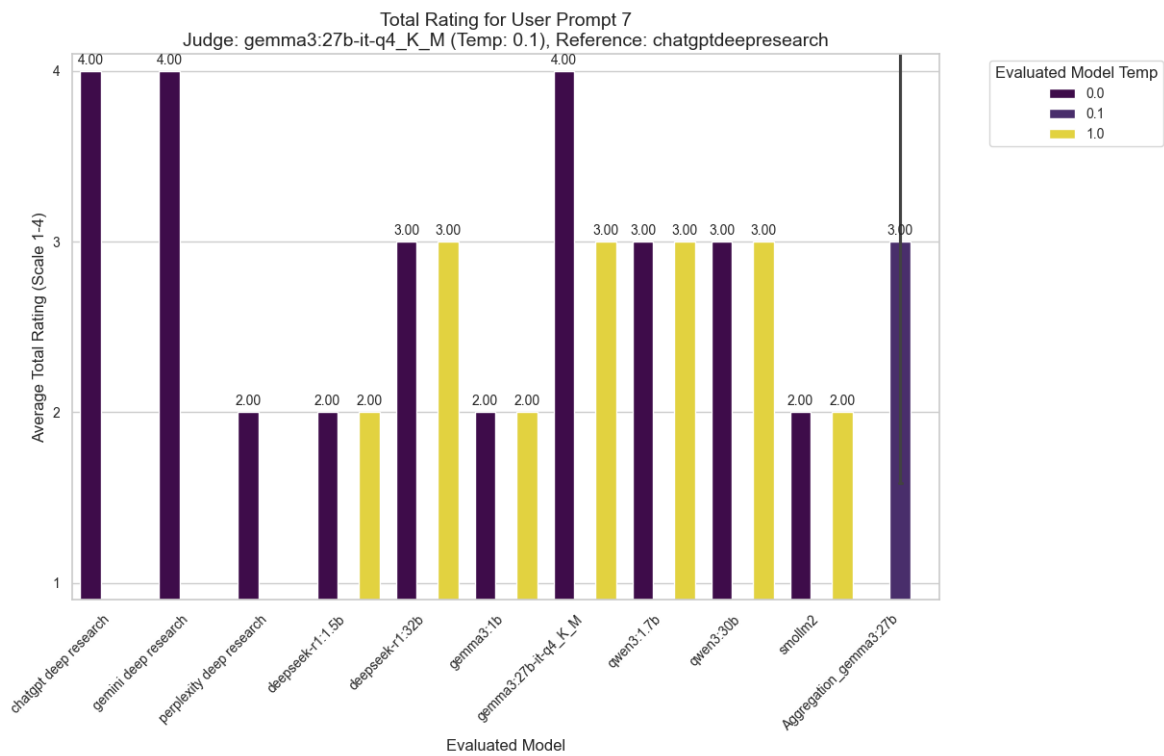


Figure 17: same style as in..., Prompt 7

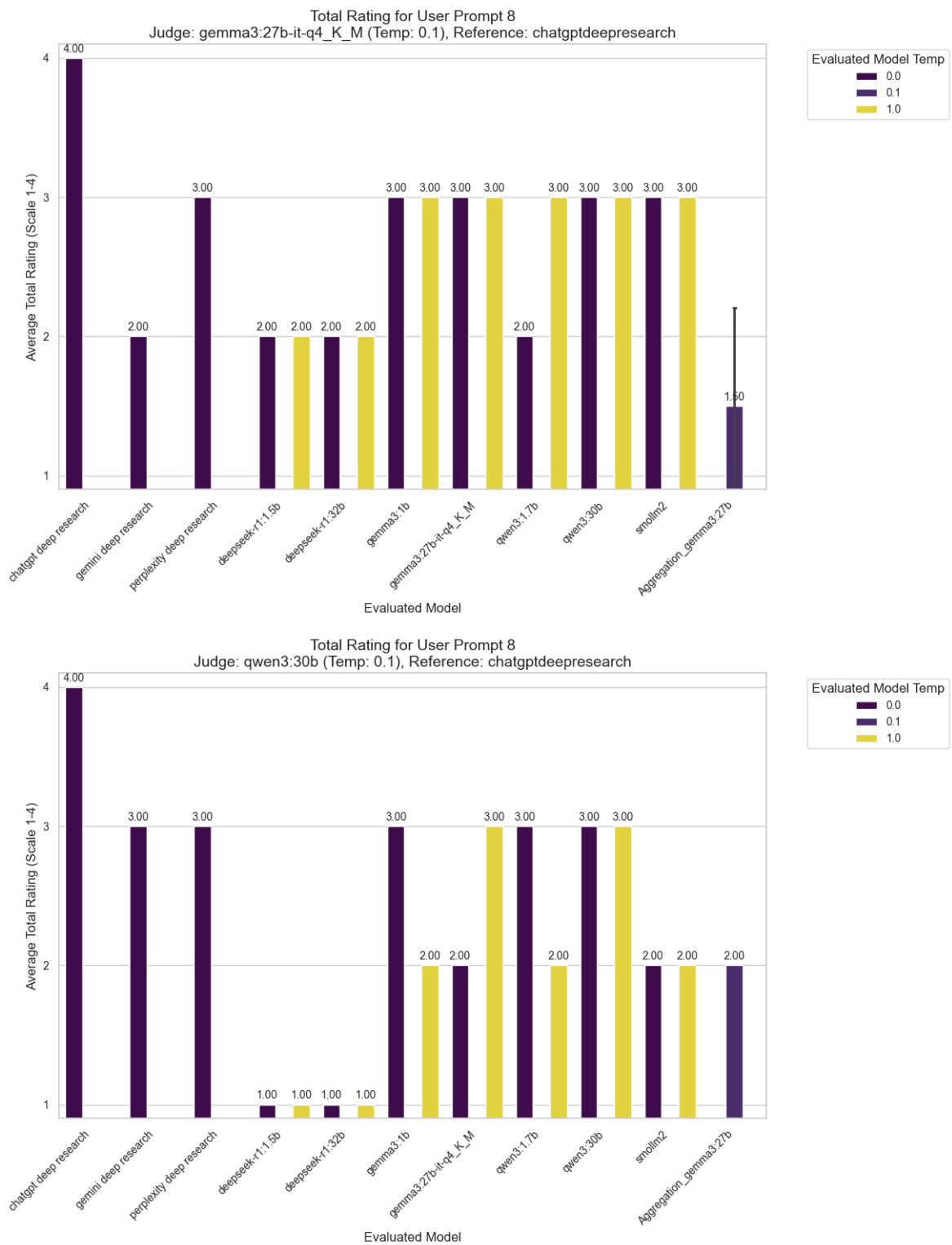


Figure 18: same style as in..., Prompt 8

10 ANNEX E - Software versions

- Python: 3.12
- PyCharm: Community Edition 2024.3.2
- Ollama: v0.9.0

11 ANNEX F - Computing Hardware used

Host No.	Description	GPU	CPU
1	Lenovo Laptop	Intel iRISx	Intel Core i7
2	Computer in Comet SmartLab	*AMD W7900	Intel Core i9

*<https://www.amd.com/content/dam/amd/en/documents/products/graphics/workstation/radeon-pro-w7900-datasheet.pdf>