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A game-theoretic framework for concurrent technology roadmap planning using best-response techniques

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***Abstract*—Technology roadmapping provides a tool for technology planning and selecting what to pursue in what timeframes. In this paper, a game-theoretic framework for technology roadmap planning is proposed to address the enumeration, selection and evaluation of possible evolution paths for technology roadmapping characterized by an iterative and competitive technology development process between companies within one tradespace. More specifically, the framework including companies as game players demonstrates the most favorable reactions to each other's technology development by approximated best response functions. Next, the selection process of optimal development paths is carried out to evaluate the possible payoffs using backward induction. Finally, a case is studied to demonstrate the feasibility of the proposed approach.**

Keywords—technology roadmapping, technology planning, game theory, best response.

I. INTRODUCTION

Nowadays, companies are confronting an increasing competition challenge [1]. Technology roadmapping is used to provide guidance to organizations in coping with growing competitive environments - it identifies company's critical needs, and helps to select the appropriate technology alternatives. Technology planning is a critical activity in industries with rapid technology evolution such as information and telecommunication technologies, as well as manufacturing, aerospace, and transportation, among others.

In this paper, we are proposing a novel game-theoretic framework for technology planning and roadmapping. We consider a group of competitors as a group of players where each player has a set of evolution strategies with several technology alternatives. Both players are considered to be rational and willing to embrace the strategy that maximizes its payoffs. The following framework makes the process of technology planning more strategically oriented in the terms of competing environment by taking into consideration the development of the other player.

Both players are willing to know the future possible design strategies at the tradespace, which are allocated in their preferable direction of developing the characteristics. The players evaluate the design strategies suggested by the framework and choose the most promising and realistic as a field for the company's Research & Development (R&D).

Various quantitative methods on technology planning and roadmapping were summarized by Heidenberger and Stummer [2]. They classified methods in several categories: benefit measurement methods; mathematical programming; decision and game theory approaches; simulation models, heuristic methods; cognitive emulation approaches. In the terms of increasing competitive environment game theory approach comes to the central stage.

Game theory is the study of rational decision-making and helps to understand how strategic interactions affect rational decisions of individual players or companies in a competitive and uncertain environment if each player aims to get the best payoff [3]. The game-theoretic approach takes into consideration company's competitive environment that might be uncertain.

II. BACKGROUND AND RELATED WORK

This section introduces key concepts of game theory, game-theoretic approaches and its application in the design of complex engineering systems.

A. Game theory and Nash equilibrium

A formal model in game theory consists of players, a set of their strategies and payoffs from each strategy combination. One of the main concepts is a nash equilibrium (NE) which represents a combination of decisions where no player has an incentive to deviate from his decision [4].

A strategy x^* is NE from the set of strategies S_i for player i with payoff function $u(x)$ if:

$$S_i\colon u_i(x_i^*, x_{-i}^*) \geq u_i(x_i, x_{-i}^*) \qquad (1)$$

The condition (1) means that each player *i*, in playing a strategy x_i^*, is playing the best response to the other's strategy choice.

B. Best-response dynamics

In best-response (BR) dynamics, each player chooses his best response to the current actions of the other player.

The best response (BR) of player *i*, $B_i(x_{-i})$, is:

$$B_i(x_{-i}) \in \arg\max u_i(x_i, x_{-i}^*) \qquad (2)$$

Then the equivalent characterization from the condition (2): a strategy x_i^* is a NE iff

$$x_i^* \in B_i(x_{-i}) \text{ for all } i \qquad (3)$$

A necessary condition for BR dynamics is convergence to NE from an initial strategy profile. It means the existence of a path induced by best-response reaction sets that connects the initial start strategy to NE [4]. Players can construct their path by building BR functions using their opponents' strategies estimation from the past games [5]. BR functions can be represented as linear or non-linear functions with one or more NE with axis of the variables [6].

C. Backward induction

Backward induction (BI) is a general concept for sequential games of perfect information. The method starts from the analysis of the latest strategies of the first player and proceeds to the search of a subgame perfect nash equilibrium (SPE). Using this information the second player can determine which strategy to choose at the second to last stage. The process continues backward until reaching the first stage of the game. The set of SPE of all game stages is a subset of NE for the whole game.

D. Game-theoretic approaches

Game-theoretic approaches are used in engineering systems design for multi-objective design and multi-agent planning problems. The theoretical and mathematical basis of games is used to abstract the processes required to design a complex system.

The model of multiobjective design has been used to analyze the convergence characteristics of the design process, and the quality of equilibrium solutions in the situation of decentralized designers [7]. Chanron and Lewis [8] assumed that decision makers follow an iterative process of communication and developed the vector, scalarization, and trade-off-curve methods to achieve multiobjective solutions.

In [9] a Coalition-Planning game formulation has been developed for self-interested players with personal goals who find beneficial the cooperation with each other to increase their personal net benefit. The research focused on cooperative self-interested agents in groups [10] and game scenarios in resource coalition [11].

Furthermore, a pure game-theoretic approach has been proposed to perform a strategic analysis of all possible player strategies and define equilibria based on the relationships between different solutions in game-theoretic terms [12]. Jordan and Onaindia [13] used game-theoretic approach for non-cooperative planning to predict the plan schedules which player will adopt so that the set of strategies of all players constitute NE.

In [14-15] product portfolio planning is considered as a combinatorial optimization problem for a competitive duopolistic market. The game-theoretic frameworks were proposed to derive NE for optimal product configuration for both manufacturers. A development planning approach using game theory and network model was suggested in [16] to address the strategy selection and evolution of weapons systems-of-systems characterized by a competition between countries.

III. PROPOSED FRAMEWORK

The novelty of this paper is the proposal of a game theory-based technology planning framework which aims at enumerating and evaluating efficient technology evolution paths taking into consideration the actions of others players as illustrated in the tradespace. The evolution paths are following the preferable directions at the tradespace of chosen FOMs and contains the future possible design strategies suggested by the framework.

A. Game model

The game model considered in this research is a sequential game with two players who possess perfect information about the past games and about each other. We use the assumption for building the first-run framework to get the results and evaluate them in these conditions. The conditions of perfect information are rarely met in the real economic environment and for that reason; the next game model will be based on the imperfect information.

These players are two competing companies that practice technology roadmapping and plan their research investments to put into a new project considering the competitor's potential moves at the technology tradespace. The players are assumed to be rational and their goal is to plan their technology development with possible design strategies in the way to maximize the possible payoffs of the strategies. The perfect knowledge assumption is the first step in the analysis; the extension of this framework to partial knowledge will be subject of future work.

The model assumes a tradespace of viable technology investment options mapped using two figures of merit (FOMs), FOM1 and FOM2, characterizing the selected technology. Future work will address the case of tradespaces mapped using multiple FOMs. The two FOMs herein are considered pertain to both players and map the players' development stage of their technology within the tradespace. Another input needed for the framework concerns Pareto frontiers projected into the future, which show all possible non-dominated technology design points at the tradespace. The current technology levels of players are supposed to be defined by the models lately put on the market. The previous development process is set as known, as it is needed for further analysis. Consequently, the historical data of the released models are the main input used for identifying the trends of company's technology development, which can be built into the future.

In real competitive markets, two competing technology companies rarely release their products at the exact same time. Before the new product is produced, the company announces their willingness to release it to the market and the approximate time. The competitors can consider this information. Using announced information about future releases and the date of the last release, the next company can determine the new product for the market.

Therefore, the whole development process of moving from one Pareto frontier to another is analyzed as a sequential game where both players move one after another at the tradespace. It is assumed the first player has a first-mover advantage that means he will choose first the best-response reaction to the current position of the second player. It is reasoned by the fact that for the current moment one of the players has released a new product and the second one is getting ready to introduce its new model. The scenario here considered is illustrated in Fig.1.

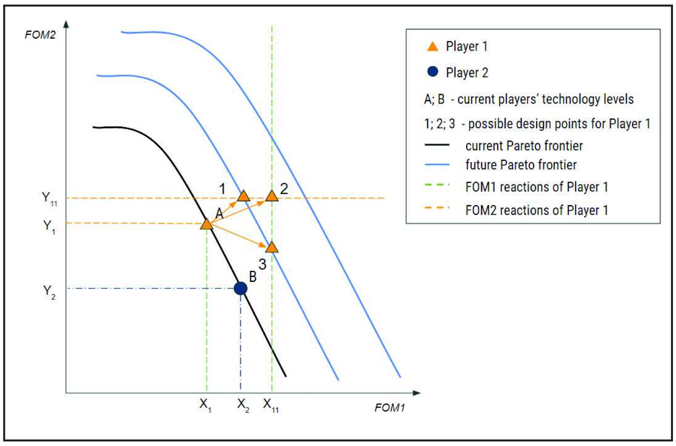


Fig. 1. Example of 2-players tradespace with predicted Pareto frontier and BR reaction set

B. *Framework*

The proposed framework consists of several steps of analyzing historical data of technology evolution and forecasting the possible development process and the possible design points into the future based on Pareto frontiers

The framework follows the next steps:

1) Step 1: Analyze historical data of player's technology development and building BR functions for both selected FOMs: the historical data from the past games, which are considered to be the previous technology development by the players (e.g. companies), is used for approximating the BR functions. The intersection of those BR functions gives the NE which both players are trying to reach in ideal conditions. The current players' positions are marked on the BR functions and the BR reactions sets are estimated by projecting on each others BR function until the NE is reached.

2) Step 2: Select the design points on the predicted Pareto frontiers at the tradespace: following their estimation, the BR reaction sets are projected on the technology tradespace. The alternative design points are determined as the intersections of the predicted Pareto frontiers and the players' BR reaction sets. Fig. 1 shows graphically the process of determining the possible evolution design points.

3) Step 3: Enumerate all possible technology evolution paths: based on the enumerated design points, Nash equilibria are mapped on the trade space. The sequential game tree is built from the defined designs starting from the 1st player's strategy set.

4) Step 4: Evaluate the evolution paths and the design points by backward induction: in this step, the comparison of alternative evolution paths is performed following the estimation of potential design points along the game tree.

5) Step 5: Identify the NE evolution technology path: the optimal evolution path is defined by backward induction on the game tree.

The result of the analysis is a set of optimal alternative design points on the Pareto frontiers for Player 1. The set can be used as a family of potential strategies for the roadmapping process. It helps to determine one of the possible ways of technology evolution. It shows how the concerned company can react in the best way to the other company's technology development.

IV. RESULTS AND VALIDATION

A first implementation of the framework was made. The following section explains the case study used for assessing the performance and validation of the framework.

A. *Case study*

The market of Graphic Processing Units (GPU) is used as a case study topic; AMD and NVIDIA are the key players in the retail market of GPUs. The dataset was taken from the open source GPU database [17], which contains a reference list of most graphics cards released in recent years and the models reviews.

The development of AMD's and NVIDIA's GPU models since 2010 is shown in Fig. 2. The technology tradespace is formed for two FOMs: theoretical GPU Performance in GFLOPS and Cost in USD.

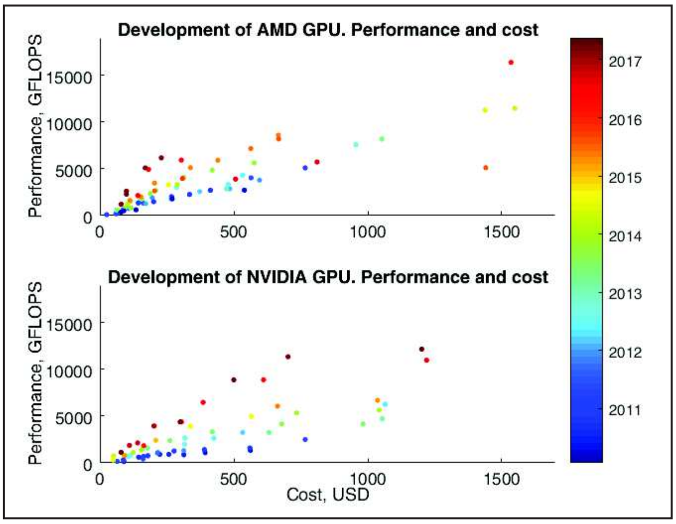
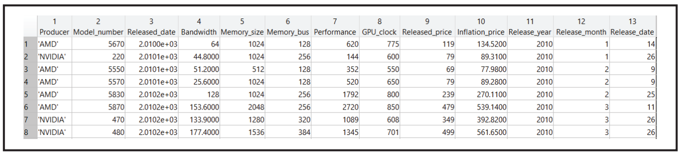


Fig. 2. AMD and NVIDIA models according to the release date.

The dataset of GPU models contains information about the main technical characteristics: bandwidth in GB/s; memory size in MB; floating-point performance in GFLOPS; the release date in the decimal year, and the released price with and without inflation in USD. Fig. 3 illustrates the example of the used dataset.



	1 Producer	2 Model_number	3 Released_date	4 Bandwidth	5 Memory_size	6 Memory_bus	7 Performance	8 GPU_clock	9 Released_price	10 Inflation_price	11 Release_year	12 Release_month	13 Release_date
1	'AMD'	5670	2.0100e+03	64	1024	128	620	775	119	134.5200	2010	1	14
2	'NVIDIA'	220	2.0101e+03	44.8000	1024	256	144	600	79	89.3100	2010	1	26
3	'AMD'	5550	2.0101e+03	51.2000	512	128	352	550	69	77.9800	2010	2	9
4	'AMD'	5570	2.0101e+03	25.6000	1024	128	520	650	79	89.2800	2010	2	9
5	'AMD'	5830	2.0102e+03	128	1024	256	1792	800	239	270.1100	2010	2	25
6	'AMD'	5870	2.0102e+03	153.6000	2048	256	2720	850	479	539.1400	2010	3	11
7	'NVIDIA'	470	2.0102e+03	133.9000	1280	320	1089	608	349	392.8200	2010	3	26
8	'NVIDIA'	480	2.0102e+03	177.4000	1536	384	1345	701	499	561.6500	2010	3	26

Fig. 3. Example of the sample of GPU dataset used for the framework.

The first approach to analyze data is to classify all models according to the technical characteristics and use the framework inside each category. As a result, the whole GPU market can be divided into 4 segments according to bandwidth, memory bus and price: High End GPU; Performance GPU; Middle End GPU; and Low End GPU. Another approach is to look and analyze the development of flagships of both companies which present the new technology or technology development of the new GPU generation or family. It is important to use the correct approach to define the sample of data which will contain the trend of BR functions.

B. Results

In this section, an illustrative example is presented. It demonstrates the analysis of competition in the development process of GPU flagship products, that is, High End GPUs for each given year.

Fig. 4 illustrates the Step 1, analyzing the historical data of the player's technology development and building the BR functions for both selected FOM of the proposed framework.

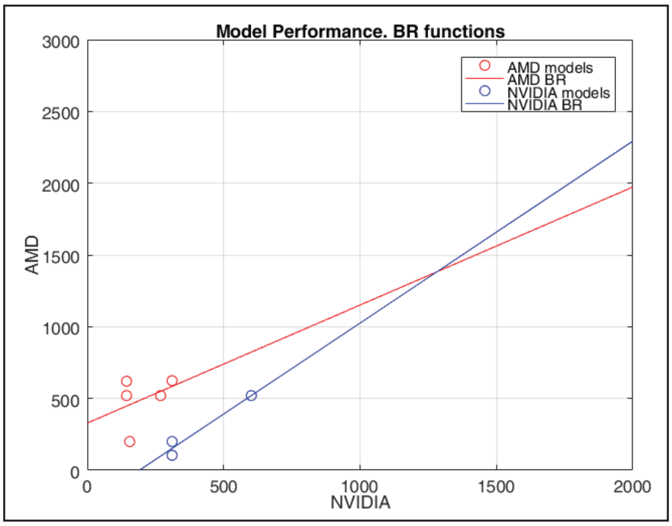


Fig. 4. BR functions of the FOM, Performance.

The BR functions for the floating-point performance are built for AMD and NVIDIA based on the chosen sample of released models which are considering as historical BR reaction sets. Fig. 5 shows the NE point for the floating-point performance as the intersection of two linear BR functions.

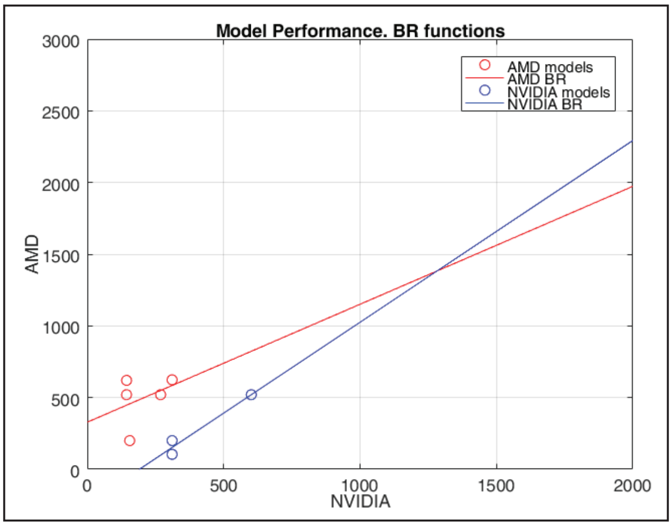


Fig. 5. Determination of NE for the chosen FOM based on BR functions

The step of estimation of BR reaction sets can be computationally consuming, depending on how far from the NE point, the players have their current technology position at the tradespace. The closer the players are coming to NE, the smaller the steps are, the more time is needed (Fig. 6).

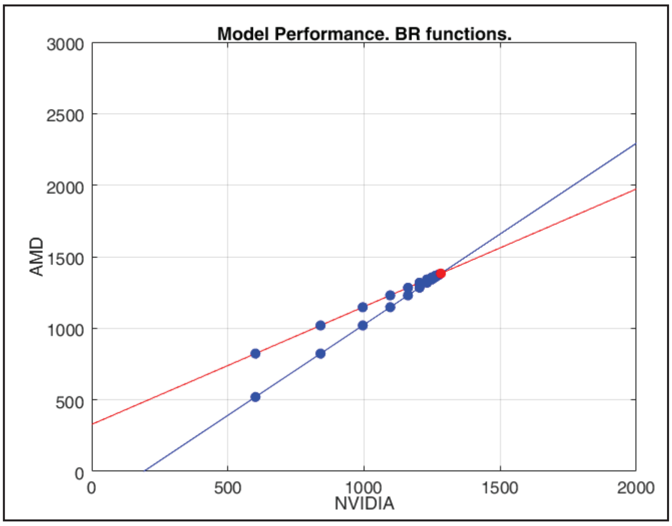


Fig. 6. BR reactions set of both players converging to the NE.

As the Pareto frontiers are needed in Step 2, selecting the design points on the predicted Pareto frontiers at the tradespace, the accuracy of the prediction influence on the alternative design points which will be evaluated later by the method. The results of the application of the proposed framework show the importance of accuracy of forecasting the evolution of Pareto frontiers over time. Pareto frontiers and BR reaction sets derive the strategy design points. The actual prediction of Pareto frontiers is not the part of this research, that is why only the part of data can be used for analysis and technology planning.

In the example of GPU development, the competition between the players is noticeable in the releases of flagships. The flagship models of each GPU generation are the core products that demonstrate the best technical characteristics of the new generation.

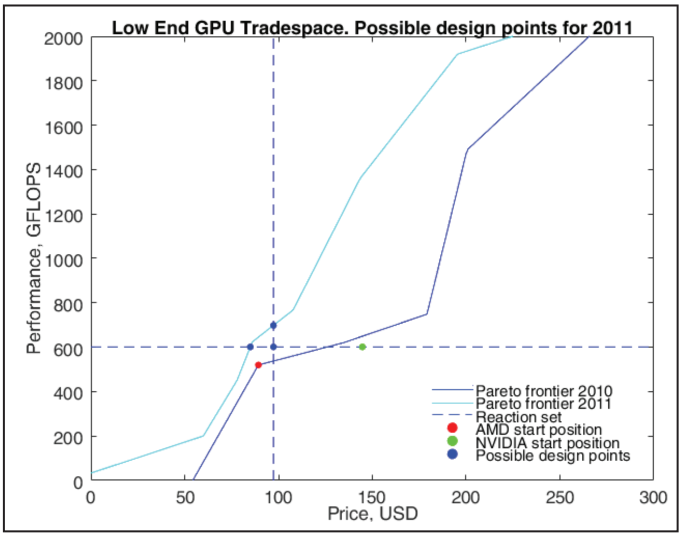
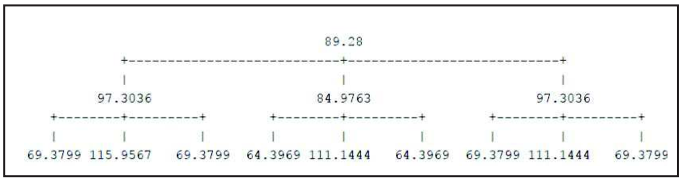


Fig. 7. GPU Tradespace with possible design strategies for NVIDIA

Fig. 7 shows the example of two not-smoothed Pareto frontiers in two subsequent years 2010 and 2011. In this case, NVIDIA and AMD are playing a sequential game of moving from Pareto frontier 2010 to Pareto frontier 2011. It is assumed NVIDIA has the first-mover advantage and reacts to the AMD position, which is taken as given. AMD's start position is the design point with performance 520 GFLOPS and cost 89,28 USD. The NVIDIA's start position is the design point with performance 600 GFLOPS and cost 144.66 USD. The estimated NVIDIA's BR price and performance results in possible evolution technology points. They are the design points with performance 698.4 GFLOPS and price 97.3 USD, 601.3 GFLOPS and 84.98 USD, 601.3 GFLOPS and 97.3 USD where NVIDIA can move from its start position. The game tree is formed out of the technology points. It shows all possible payoffs for the certain stage of one of the players. The following game tree can be built for one or both FOMs depending on whether one or two FOMs are considered during BI. From the results, it can be seen that the player can at most converge to the future Pareto frontier with the jump in one of the considering FOMs or move to the visible part under Pareto frontier by trying to improve both FOMs. Fig. 8 shows the game tree built for possible performance reaction sets of both companies where the top of the tree is NVIDIA's start performance.



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                                89.28
          +---------------------------+---------------------------+
          |                           |                           |
       97.3036                     84.9763                     97.3036
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 |        |         |        |        |         |        |        |         |
69.3799 115.9567  69.3799  64.3969 111.1444  64.3969  69.3799 111.1444  69.3799
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Fig. 8. Game tree for GPU performance.

One of the essential steps in the framework is the approximation of BR functions. The reliability of BR functions depends on the number of data points used for its estimation and how easy the trend of the functions can be defined. During the timeframe from 2010 until 2017 only around 200 of different GPU models were released and only around 10% can be studied as flagships of GPU generations. This sample size (~20 data points) is not enough for highly reliable BR functions. Therefore, the present GPU case study suggests that the proposed framework requires large datasets to be validated, but it will require another approach for taking a sample from the initial dataset.

C. Validation

The purpose of validation analysis is to ensure that the proposed framework suggests sufficient evolution technology paths.

If historical data exist (in our case), part of the data is used to build the model and the remaining data are used to determine and test whether the model behaves as the system does [18]. Hence, the main approach of validation analysis is backward testing on the historical data. The initial dataset is cut by the certain year and the models released before the cut year are used to predict future player's moves at the tradespace and afterward compare the result design points to the known historical models.

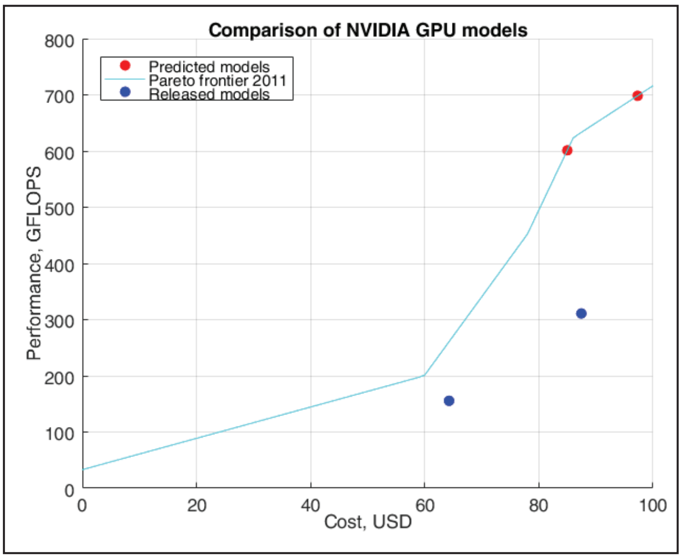

Fig. 11. Comparison of GPU models predicted and released by NVIDIA.

The NVIDIA predicted design points are models with performance 698.4 GFLOPS and 601.3 GFLOPS, and price 97.3 USD and 84.9 USD respectively. The NVIDIA released models in 2011 are models with performance 311 GFLOPS and 155.5 GFLOPS, and price 87.44 USD and 64.26 USD respectively. If assume the first predicted model corresponds with the first released model (Fig. 11), then the biggest difference in performance is 445,8 GFLOPS what goes to most nearly 3 times difference; the smallest difference is by the factor of 2. In that order the biggest price difference is 20.7 USD, meanwhile, the smallest is 9.8 USD what is 11% of the difference. The framework shows better results for the FOM price. The difference might be the result of the listed external factors, which were not taken into consideration in the framework. Taking the sample from the initial dataset can be considered for the technical characteristics like the floating-point performance, and the framework should be tested on bigger datasets of different technologies and for various technical characteristics.

V. CONCLUSION

This research proposes a novel game-theoretic approach for competitive technology planning in the terms of technology roadmapping. A competitive planning framework informing technology roadmapping has been developed, assuming a competitive environment modeled as a sequential game between two players with perfect knowledge. The proposed framework supports decision-makers in strategically account for potential competition moves in their technology roadmapping process. A case study is presented based on a publicly available dataset of GPUs, focusing on flagship GPU products. The results of the application of the proposed framework show the importance of correct samples for building BR functions and the importance of the accurate construction of them.

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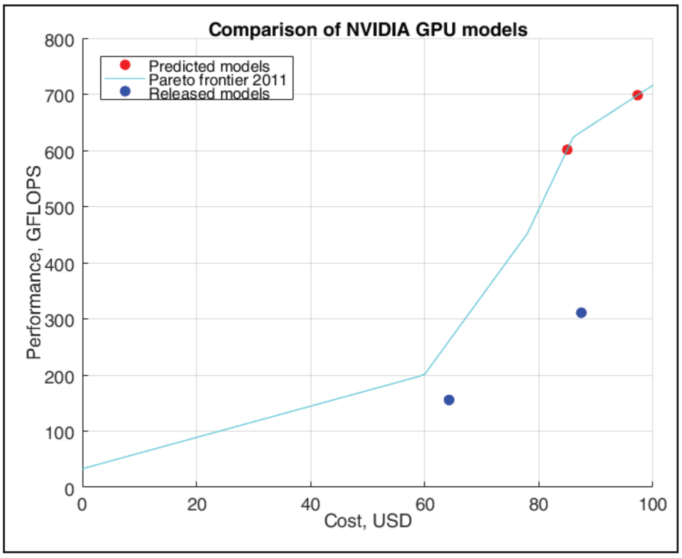

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