HOW TO BUILD AN AUCTION MACHINE

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Abstract. The Federal Communications Commission (FCC) auction was a new kind of auction used for the allocation of licences for the use and exploitation of the electromagnetic spectrum in The United States. This auction set a methodological standard of design and engineering in economics; its design adopted some properties from the traditional English and Dutch auctions and it also add new innovative properties, such as multiple rounds where bidders can return unwanted items. Unlike the English and the Dutch auctions, the FCC auction was designed and built by social scientists. The large revenue it raised was hailed as a proof of success of mechanism design theory. This success led some European governments to hire mechanism designers for the design and implementation of similar auctions for the allocation of licences on the electromagnetic spectrum. The success was not only due to the knowledge available from mechanism design theory but also from the practical knowledge experimental economists have, they performed the experiments testing the rules and mechanisms, which produced data crucial for the design and the implementation of the new auction. In this article, I present a methodological account of the FCC auction design discussing two main components of it, namely the blueprint produced by mechanism designers and the experiments performed for producing the data missing in the blueprint. I also evaluate this blueprint using the types of design and principles, namely minimal analogy and type-hierarchies.

1. INTRODUCCION

I characterise the method used by experimental economists designing the FCC auction as the method of *experimental parameter variation*, which I take from aeronautical engineering. The introduction of the method of experimental parameter variation allows philosophers to pay attention to practical knowledge, or knowledge of practices, as opposed to propositional knowledge. Practical knowledge has been largely ignored in epistemology and in the philosophy of science. Science is not only the knowledge of theories, laws and inferences; there is a vast array of practices, some of them highly successful and sophisticated. Engineering and experimental methods have been mostly developed in the natural sciences, where they have been growing in size and sophistication. In economics and other social sciences these methods have been developed only recently, and there seems to be an increasing demand for more experimental and engineering knowledge in these sciences.

The FCC auction blueprint is a multipleround simultaneous ascending auction. This blueprint was produced by three mechanism design theorists, Paul Milgrom, Robert Wilson and Preston McAfee. I characterise this blueprint as partly dirigiste and oligopolistic, and explain why on four of the five principles of design advanced by the philosopher Nancy Cartwright, this blueprint falls below the standard by leaving some gaps in the design. Using the rules on minimal and maximal analogy and type-hierarchies, I argue that this blueprint is a case of minimal analogy, and therefore it is a progressive design within the type-hierarchy of auctions.

In section 2, I introduce and describe the method of experimental parameter variation from aeronautical engineering. For this, I rely on the work from Walter Vincenti, an engineer who illustrates this method using the experimental work the mechanical engineers William F. Durand and Everett P. Lesley did in the

1920s, when they tested a large number of new air propeller prototypes using a wind tunnel. The data obtained were crucial for the manufacturing of propellers ready to be assembled in a new model of aircrafts superior to those available at the time.

In section 3., I show how the method of experimental parameter variation can be extended to experimental economics, and in particular to the experiments performed by Charles Plott and his team searching for data crucial for the successful implementation of the FCC auction. The experimental work done by Plott and the data obtained filled the gap left in the blueprint submitted by Paul Milgrom, Robert Wilson and Preston McAfee.

2. THE FCC BLUEPRINT

Multiple-round simultaneous auctions are a new kind of auction designed and implemented by the mechanism design theorists and experimental economists. The creation of this new kind of auction came as a product of a call made by the US Federal Communications Commission (FCC) in 1993 for a new more efficient mechanism to be used for the allocation of licences to telecommunication firms for the use and exploitation of the electromagnetic spectrum.

A multiple-round simultaneous auction is a social machine consisting of three main mechanisms, namely a simultaneous market, ascending biding and multiple rounds. In a multiple-round simultaneous auction, several markets are open at the same time, so any bidder can place any number of bids in different markets. The markets run in rounds and remain open until the bidders have accomplished the best purchase by selling back some items and buying new ones. These properties of the auction allow a highly efficient allocation of licences and the maximisation of revenue for the auctioneer, which in this case was a government institution. The design of this new auction relied on the pioneering work of the economist William Vickrey, who designed an auction of multiple items with a sealed bid, where the auctioneer is also a government agency just like the case of the FCC where multiples licences are auctioned. With this design, Vickrey was trying to solve the problem of imperfect competition in free markets, which can lead to undersupply and oversupply of commodities. An auction of multiple items with a sealed bid provides the blueprint of a social machine, whose mechanisms could attain competitive equilibrium prices of commodities.

The design and successful implementation of the first multiple-round simultaneous was hailed as an outstanding achievement almost exclusively due to game theory, which clouded the important and distinctive engineering work done by experimental economics. The philosopher Francesco Guala made a significant advancement showing the crucial contribution made by experimental economists; he presents the case mainly as a problem of logic, where inferences made in the laboratory have to be extended to the outside world.[1] Unlike Guala,

[1] F. Guala (2005), pp. 178-181, 194-199.

I present the case as a methodological problem concerned with design and blueprint-making methods. In particular, I argue that the method of experimental parameter variation was used by experimental economists in order to produce data essential for the design and implementation of the FCC auction.

As part of the decentralising trend of public assets and services in 1980s, the US Congress decided to look for a new and more efficient mechanism for the allocation of licences for the use and exploitation of the airwave space, which would lead to the provision of mobile communication with cellular telephones and radio systems, and the transmission of data with fax machines. Until 1982 these licences were allocated using an administrative hearing process known as the 'beauty contest', in which each applicant had to persuade the FCC of the benefits of adjudicating a licence to them. This allocation procedure was slow, opaque and highly bureaucratic. A first attempt at replacing the beauty contest was made by introducing a lottery where licences were randomly allocated to the applicants. This new mechanism was fast, transparent and simpler; however it created strong inefficiencies by allocating licences to applicants who have no real interest in exploiting the licence. This created a secondary market where licences were sold and resold creating large profits for private individuals, and a loss in revenue for the government.

The US Congress was aware of the disastrous experience in New Zealand and Australia in the early 1990s, where licences were allocated using first-price and second-price sealed-bid auctions. These auctions were chosen without asking for scientific advice; they produced large losses in the government's revenue, and they also prompted strong criticism from the public and rival political parties.[2] The US government looked for scientific advice issuing in 1993 a 'Notice of Proposed Rule Making', where the FCC advanced an initial design of an auction in two stages, expecting replies and comments mainly from economists and game theorists. In order to prevent an oligopolistic distribution and promote economic equality, the original policy set by the Congress considered a distribution of licences to minority-owned and women-owned companies, small businesses, and rural telephone companies. However, the final design excluded these groups by allocating the licences to those bidders holding the highest bids, which led to an oligopolistic distribution with an increase of inequality.

Game theorists model auctions as non-cooperative games played by self-interested utility-maximising bidders. This game assumes a solution under Nash equilibrium, namely that given everyone's moves, no player can be better off than she currently is by shifting to a different strategy. There were two important problems mechanism design theorists faced in designing the new FCC auction. The first one was related to the complementary character of licences in contiguous regions of the spectrum. The second one was related to the existence of perfect substitutes in different portions of spectrum. Given these two properties, the value of any package of licences would vary according to number and combination of contiguous and non-contiguous portions of the spectrum.

[2] See J. McMillan (1994).

Moreover, a number of further conditions such as affordable technologies and operation costs had to be considered in the design. These further conditions added to the perfect substitution and complementary values produced an excessively large number of packages with almost each of them having a different value.

Generally, auction models assume a common value of the items, that is to say, the value of the auctioned item is assumed to be the same for every bidder but unknown to all. The design of auctions where items have different values for different bidders was in an early stage. The economic theory available at the time did not provide the means for estimating the different outcomes of an auction where the items have different values. Some insights pointed to the highly problematic nature of items with complementary properties, whose unstable value produces different Nash equilibria with no clear indication as to which of them is optimal. Therefore, the design of the FCC auction represented an important challenge due to the lack of data on important aspects which no theory could provide. The situation is the same to that of the design of the new air propellers to be discussed in the next section, where data which the blade element theory could not supply were lacking.

The FCC hired the economist John McMillan, who suggested an auction in two stages. In the first stage, the licences would be auctioned in packages using a sealed bid, and in the second stage only individual licences would be auctioned. This mechanism seemed to solve the complementarity problem since those bidders who value packages over individual licences would place high bids in order to get more than one licence. In the second stage, bidders with a preference for individual licences would equally place high bids. In both cases, an auction with two stages seemed to be efficient by allocating licences to bidders who could maximise their use and exploitation based on their willingness to pay more for them. This design was supported by the National Telecommunications and Information Administration (NTIA), a public institution advising the government and the FCC, which had also suggested package-bidding after getting the advice from the economist John Ledyard, who had worked on the design of combinatorial auctions.[3] Unlike the beauty contest and the lottery, this design was scientifically supported. Because this design was fully controlled by FCC and the NTIA, and because these two government agencies decide the combination of licences in each package, the design is dirigiste, that is to say, it contains some properties of central planning.

Some telecommunication firms were critical of package-bidding as it was not competitive enough because for it prevented some bidders from purchasing some licences, which created an unfair advantage for those who may be allocated with a large part of the spectrum; they thought that an open bid could provide equal bidding opportunities to all. Telecommunication firms realised that a bad design could actually affect their own interests by creating unfair and inefficient allocation, and so they decided to hire their own scientific advisors. The economists Paul Milgrom, Robert Wilson and Charles Plott were hired by Pacific

[3] See J. Ledyard et. al. (1997).

Bell; Jeremy Bulow and Barry Nalebuff by Bell Atlantic; Preston McAfee by Airtouch Communications, Robert Weber by Telephone and Data Systems; Mark Isaac by the Cellular Telecommunications Industry Association; Robert Harris and Michael Katz by Nynex, Daniel Vincent by American Personal Communications, Peter Cramton by MCI; and John Ledyard and David Porter by the National Telecommunications and Information Administration.[4]

Paul Milgrom and Robert Wilson put forward a new design which they called 'simultaneous ascending-bid auction'. Separately, Preston McAfee put forward a similar design. A simultaneous open auction constituted the answer to the concerns voiced by private firms on package-bidding with a sealed bid, and it also represented an improvement on the two stages considered in the FCC initial design.

In a simultaneous open auction several markets are open at the same time and bidders can participate in all of them at once. This was a true innovation in auction design. Unlike a sealed bid, an open simultaneous auction allows each bidder to monitor the behaviour of other bidders. This valuable information enables her to assess her chances of buying the combination of items she prefers. During the auction, bidders can move freely from one combination to another by selling back to the market those items over which their preference has changed, until they accomplish a combination with the highest value. Another important advantage of this new design over a sealed bid is that it helps prevent the winner's

[4] See J. McMillan (1994); F. Guala (2005), pp. 167-168.

curse, that is to say, the possibility of overbidding. This can be prevented because bidders can monitor the pricing behaviour of others.

Besides the open character of the new auction, simultaneous bidding on several markets all opened at the same time was also another important innovation. In the traditional English ascending auction, items are auctioned one by one starting with a low price, and bidders continue making offers until the market is closed, which usually occurs when no new offer is put forward. Therefore, the possibility of getting a combination of items is not directly made available. This could only occur if a second market is open where items are resold but not all items may be there, and prices would also increase because of the costs and time involved in opening a second market.

In the traditional Dutch descending auction time is fixed and items are sold in packages starting with a high price, which prevents other bidders from purchasing individual items they have a strong preference for. Again, a secondary resale market could be open but the same problems of time and cost rising would appear. Therefore, a direct sale in one single market represents a more efficient design. Because in the Dutch auction prices start high and time is limited, demand may be prematurely terminated affecting prices and efficiency in the allocation of items. A simultaneous ascending auction prevents this situation by allowing more time holding a long round until no new bid is put forward. It also prevents a resale in expensive secondary market by providing different rounds, where bidders can sell back to the market any number of items as well as buy new ones until they are satisfied with a package.

The final blueprint was prepared and submitted by Paul Milgrom, Robert Wilson and Preston McAfee. It contained the descriptions of the three new mechanisms, namely a simultaneous market, ascending biding and multiple rounds. This blueprint can be evaluated using the types of design discussed in chapter two, namely libertarian and dirigiste, and the five principles of design and engineering advanced by Nancy Cartwright. Also, a further evaluation can be made using the distinction between minimal and maximal analogy, and by constructing a type-hierarchy.

Because the electromagnetic spectrum is controlled and fully regulated by the state through the FCC and the NTIA,[5] and because these two agencies still controlled part of the design, this blueprint retained some aspects of central planning. The blueprint is oligopolistic because by allocating the licences to those holding the highest bids, it excludes minority-owned, women-owned companies, small businesses and rural telephone companies, so such a design fosters the domination of the market by a small number of firms.

The contrast between the traditional English and Dutch auctions and the new FCC auction with multiple-rounds, simultaneous markets and ascending

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[5] The design of FCC auction was made under the USA Communications Act of 1934, which defined the electromagnetic spectrum as publicly-owned resource and prohibited any private ownership of it; those granted with a licence were defines as 'public trustees'. The law rapidly changed in 1996 after the first FCC auctions were run extending the rights of the licence holders, who could now hold the licence almost permanently; see K. Corbett (1996) for details.

bidding provides a further case and illustration of the distinction between traditional and artefactual institutions. The contrast between traditional and artefactual institutions can be made between the International Gold Standard, and the International Monetary Fund. Like the Gold Standard and other cases of commodity money, the Dutch and the English auctions were also created without the help from scientists, that is, without using mechanism design theory and neoclassical economics. In contrast, the FCC auction is the product of scientific design, it is a social machine made up of three main mechanisms assembled to create a whole new machine. Friedrich Hayek (1943, 1978) argued against the creation of an international monetary institution endowed with the power to dictate national economic policies and produce fiat money, as it had been suggested in the blueprint put forward by John Maynard Keynes (1923, 1943). This was only a case of a general argument Hayek made against design and engineering, which he described as 'constructivist', and against dirigisme, that is, against central planning and control.

The first design of the auction in two stages where the FCC and the NTIA decided on the combination of licences in each package was a case of dirigisme with central planning. Such dirigisme was prevented by the action from telecommunications firms who hired scientists to produce designs where their own interest were fostered and protected. Therefore, the final blueprint became partly libertarian by giving those firms the power to decide how to form their own licence packages. A full right-libertarian blueprint would have considered giving private firms the control and ownership of the electromagnetic spectrum instead of just giving them a licence. This would have led to the extinction of the FCC and the NTIA or the reduction of them to agencies supervising the quality standards of the telecommunication services. In contrast, a blueprint which includes licences for minority-owned, women-owned companies, small businesses, and rural telephone companies as it was originally planned would have been at least partly egalitarian, although still dirigiste.

A sharper contrast can be made with the blueprints from left-libertarianism and a property-owing democracy, where direct widespread ownership of the electromagnetic spectrum among the unemployed, low-income families and other worst-off groups could be considered. In this case, without having to wait for the distribution of the revenue raised by the FCC auction and taxes through welfare institutions under the blueprint submitted by Milgrom, Wilson and McAfee. Additionally, the size of the welfare state would be reduced and also the power and size of central government, which in this case is represented by the FCC and the NTIA. The contrast with left-libertarianism and a property-owing democracy can only be generic because blueprints from these positions are virtually inexistent.[6] Mechanism design theory and experimental economics are dominated by neoclassical economics and welfare economics. I argue for a methodology of design and engineering in the social sciences, which can be

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[6] For recent views on left-libertarianism see P. Vallentyne and H. Steiner (ed.) (2000). John Rawls (1999, pp. xiv-xv, 242-251; 2001, pp.135-140) argues for a property-owing democracy.

detached from their current ideological and historical biases, and can therefore be made available to other positions; particularly those where design and engineering are poor or inexistent.

A second evaluation can be made by using the rules on minimal and maximal analogy and type-hierarchies. The magnetic force models from James Maxwell and William were presented as examples of maximal and minimal analogies. The model from Thompson was more progressive because by describing the magnetic force as a field it minimised the analogy with the mechanical Newtonian paradigm, while the model from Maxwell maximised such an analogy. This analogy was further appreciated by building a type-hierarchy. In a similar way, minimal and maximal analogies can be applied to blueprints also building a type-hierarchy.

Eileen Way (see Harré 1995) defines a type as ‘a set of individuals each of which has certain properties which are numerically identical with those in other sets of higher type’. Because types have a nominal status, the relationship they hold with their tokens cannot be that of ‘qualitative identity’, which only holds ‘between the relevant concrete properties of each particular’[7]; numerical identity does the job of establishing the relationship needed between tokens and the types. For instance, a ‘gold coin’ is a token whose properties are numerically related to those contained in the ‘commodity money’, which is a nominal representation. Types are ordered according to their level of generality forming a pyramid or a

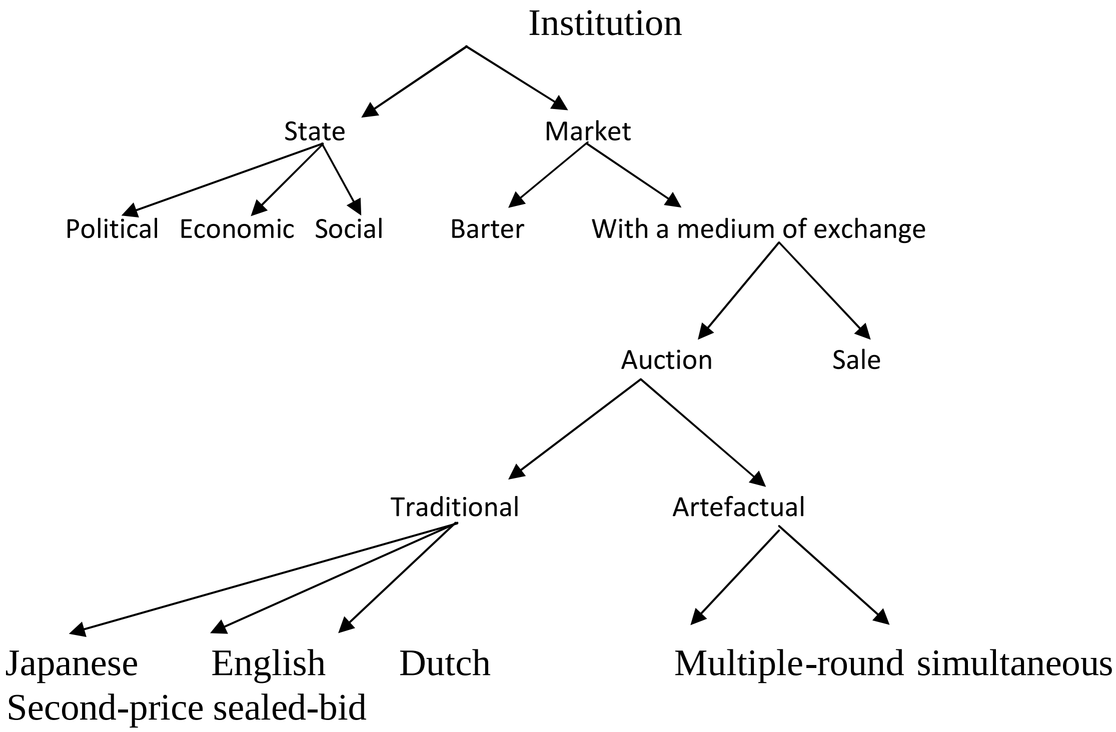
[7] R. Harré, J. L. Aronson, E. C. Way (1995), pp. 15-16.

three-like classification. Because commodity money is a traditional kind of money distinct from fiat money, is it necessary to distinguish between traditional social kinds and artefactual social kinds. Traditional kinds rely on custom and knowledge accumulated across different generations without the intervention of science, while artefactual kinds are a product of science, design and engineering. The same distinction can be applied in the natural sciences, for instance in chemistry where natural and synthetic elements are distinguished, or in synthetic biology where a distinction is made between natural and synthetic DNA.

Tyype-hierarchies can be graphically presented using a tree-like shape placing at the top the type with the largest extension, which is called a supertype. The same graphic presentation can be made for the multiple-round simultaneous auction placing 'institution' as the supertype, and also by distinguishing traditional from artefactual auctions:[8] See figure 1 below:

[8] Different criteria can be used for classifying auctions and there are further types of them, see P. Klemperer (2004), and P. Milgrom (2004).

Figure 1. A partial type-hierarchy of multiple-round simultaneous auction:



Although, there is no paradigm shift in the design of the multiple-round simultaneous auction, significant progress was made in the design of artefactual auctions, which started with the work of William Vickrey (1961), who designed the second-price sealed-bid auction. The multiple-round simultaneous auction is an artefactual auction which combines aspects of the English and the Dutch auctions, namely ascending bidding and the combination of items in packages, adding to them multiple rounds, the return of any unwanted licences, and bid increments decided by the auctioneer. The similarities with the English and the Dutch auction constitute the positive analogy, and multiple rounds, the return of unwanted licences and bid increments constitute the negative analogy. Because the size of the negative analogy is larger, the blueprint is a case of minimal analogy, and therefore it is a progressive design within the type-hierarchy. Design by analogy does not exist as part of the methods in mechanism design theory, it is a topic to be developed both in philosophy and the social sciences.

A third evaluation of the Milgrom-Wilson-McAfee blueprint can be made using the *five principles for blueprint making* from Nancy Cartwright, (2007) namely:

(i) The parts that make up the machine, their properties and the separate capacities.

(ii) How the parts are to be assembled.

(iii) The rules for calculating the outcome from the joint operation of the assembled parts.

(iv) What counts as shielding.

(v) How the machine is set to run.

Cartwright used the blueprint of a repudiation-proof contract from Oliver Hart and John Moore (1994) to illustrate how these principles work and how their demands should be met. With the help of equilibrium theory and the rules for renegotiation designed by Hart and Moore an optimal equilibrium can be accomplished by decisions made by the players, which solves the inefficiency created when the contract is repudiated. Hart and Moore's blueprint only meets the requirements from the first three principles because it describes the parts of the machine, namely two individual players the investor and the entrepreneur both displaying specific psychological capacities: self-interest, greed, perfect and costless calculation, and full rationality. Other parts are structural or external to both players such as the same discount rates, certainty in all operations, rules for renegotiation, and the existence of a frictionless second-hand market for the physical assets of the project. The structural parts and the players are assembled in a single game with two stages, one with an initial negotiation and agreement on a certain distribution of the surplus, and a second one when repudiation of the contract occurs and the surplus is now divided in equal parts. However, the blueprint does not provide information on how to shield the new contract and how to implement it.

The evaluation of the multiple-round simultaneous auction blueprint is less positive. The parts of the machine were known, namely self-interested telecommunications firms with high purchasing power and the FCC as a greedy government agency wanting to maximise the revenue. The structural parts were also known, which consisted of rules defining the three main mechanisms, namely a simultaneous market, ascending biding and multiple rounds. Although, Milgrom, Wilson, McAfee and others were confident that the auction would work, there was no knowledge on how to put all the different parts together and how to set the whole auction running; and there were no means either for getting a reliable calculation on the outcome. There were concerns about collusion among the bidders and attempts from them to outwit the rules, however no precise shielding against these possibilities was part of the blueprint. McAfee and Milgrom actually explain that ‘the spectrum sale is more complicated than anything in auction theory. No theorem exists–or can be expected to develop–that specifies the optimal auction form.’[9]

Two of the main problems were complementarity and perfect substitution of the licences, and a solution using Nash equilibrium was not feasible. For instance, because licences packages would be formed, the existence of complementary values means ‘that market-clearing prices may not exist. Equilibrium is likely to exist if the buyers have similar views about how the goods should be aggregated, whereas it may not if they disagree about what constitutes good aggregations.’[252] The solution to this and other problems was provided by the experimental economist Charles Plott and his team, who devised the experiments which produced the data needed using the method of experimental parameter variation. Milgrom himself recognises this when he writes that ‘much of what is known about multi-unit auctions with interdependencies comes from experiments.’[10]

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[9] P. McAfee and J. Milgrom (1996), p. 171.
[252] *Ibid.*, p. 172.
[10] J. McMillan (1994), p. 151.

3. EXPERIMENTAL PARAMETER VARIATION

The engineer Walter G. Vincenti has produced a methodological account of aeronauticalengineering, where he surveys different historical episodes of engineering research and design to illustrate a number of methodological practices. One of the most suggestive methodological practices he identifies in this survey is Experimental Parameter Variation (EPV), which he defines as: 'the procedure of repeatedly determining the performance of some material, process, or device while systematically varying the parameters that define the object of interest or its conditions of operation.'[11] He explains that this method is distinctive of engineering in contrast to scientific theories:

> Experimental parameter variation is used in engineering (and only in engineering) to produce the data needed *to bypass the absence of a useful quantitative theory*, that is, to get on with the engineering job when no accurate or convenient theoretical knowledge is available. This is perhaps the most important statement about the role of parameter variation in engineering.[12]

Vincenti illustrates this method by discussing the work from the mechanical engineers William F. Durand and Everett P. Lesley, who performed extensive experimental research between 1916 and 1926 with the purpose of designing and

[11] W. Vincenti (1990), p. 139.
[12] *Ibid.*, pp. 161-162.

producing new fixed-pitch air propellers superior to those available in Europe. Prior to the development of variable-pitch propellers in the 1930s, only fixed-pitch propellers were used in aircrafts. Since the shape of a fixed-pitch propeller could not be changed during different flight conditions, they were optimised for cruise, climb or take-off depending on which one was most critical for the airplane mission. Choices were also made selecting a propeller which could attain a compromise general performance, where no aspect was optimised.

In the United States no significant research had been done since the pioneering achievements of the Wright brothers in the first decade of the twentieth century. Although, some information on air propellers was available at the time, no systematic data existed which could support a new design. Only a few results were available from the experimental work done by Gustave Eiffel, a French engineer who had developed a new type of wind tunnel for experimenting with three families of different propellers, with each family containing four types of propellers. Experimental engineering research work on air propellers began in England, France and Germany around 1910. By 1913 in England comparisons were made between previous theoretical work and experimental data showing that theory was only useful for the general qualitative aspects of design. Accordingly, the quantitative part would have to be developed from data to be obtained in the laboratory.

In contrast, the amount of systematic data on marine propellers was significantly larger. By 1905 William Durand had produced experimental results on forty-nine different prototypes using the method of experimental parameter variation. By 1908 in England, Robert Froude had reported results on thirty-six marine propellers. In the United Stated this was followed by a hundred-and-twenty more results reported by David Taylor in 1910. Because of the availability of data on marine propellers, Durand and Lesley relied on them for their research on air propellers.

In addition to the existing experimental data on marine propellers, the blade element theory from Stefan Drzewiecki was also available. This theory divides the blade of a propeller into a large number elements at different radii, and each element is modelled as a small aerofoil moving in a straight line with a velocity determined by three components, namely the forward speed of the propeller, the tangential speed of the rotating element, and a secondary speed of flow induced by the aerodynamic action of the propeller itself. Then, the forces of each element at its appropriate velocity are estimated from experimental aerofoil data. Finally, the performance of the propeller is determined by summing all those forces.

One of the main problems Durand and Lesley faced was the calculation of the secondary flow induced by the action of the propeller. They used the blade element theory neglecting this secondary force and other complicating effects. By doing this they were able to calculate the performance of eighty two-blade air propellers by varying the parameters in a theoretical fashion. They compared these results to those obtained through experimentation finding that the general trend was same, while the quantitative values were substantially different and erratic.[13] This discrepancy between theory and experiment is very important because it shows the limits of theoretical knowledge for purposes of design. Theoretical knowledge is frequently insufficient for design; no reliable and efficient design can exclusively rely on it. The theoretical calculus of trends in the performance of air propellers made by Durand and Lesley is analogous to calculus of behavioural tendencies made by experimental economists, who also produced experimental data for design which a theory cannot provide. This is shown in the next section with the design of the multiple-round simultaneous auction.

Durand and Lesley produce new data by testing different prototypes of propellers made of different materials and with different shapes by systematically varying the parameters within the range of practical concern, defined mainly by a set of foreseeable flight requirements and conditions. They define the performance of a fixed-pitch air propeller as the function of two different sets of parameters, namely the conditions of operation and the geometrical properties of the propeller. The former includes the forward speed V and the revolutions per unit time n; the latter includes the diameter D and a number of ratios r_1, r_2, … etc. which contain information on the geometrical shape. The propeller performance P is determined by the following equation: $P = F(V, n, D, r_1, r_2, \ldots)$. The description in the equation is approximate because it leaves out complicated

[13] *Ibid.*, p. 155.

secondary effects from viscosity, compressibility of the air and the elastic bending of the propeller. Given the aim of the design, these effects can be neglected. Once the value range of concern has been fixed and the list of particular values has been established, 'parameter variation for the propeller consists of systematically varying the values of the parameters within the parentheses and measuring the resulting variation of propeller performance.'[14]

Because of the crucial role of the geometrical shape of the propeller, the ratios became the relevant parameters to be tested. After some preliminary tests, Durand and Lesley selected a diameter of three feet for all the small-scale prototypes and they established five parameters of relevance defined by ratios r_1 to r_5. The most important parameter was the mean pitch ratio, which is a measure of the angular orientation at some standard representative radius relative to the plane of propeller rotation of the blade section. This parameter is particularly important because the larger the mean pitch ratio, the higher is the angular orientation of all blade sections. The other four parameters contained information on the distribution of the pitch ratio along the blade and the type of blade section. They chose three equally spaced values of mean pitch ratio and two values of each of the other four parameters. Using all possible combinations of values, Durand and Lesley obtained forty-eight different propeller models, which were distributed in a representative way over the field of design. Using a wind tunnel,

[14] *Ibid.*, p. 148.

each model was tested using a prototype through a series of values of rotational speed *n* at distinct values of forward speed *V* to determine its performance *P*. Those with the highest value were selected.

This was the initial and fundamental stage of the research, where the method of experimental parameter variation was crucial for obtaining data needed in further stages until the completion of the full design, construction and final test of the new propellers. The research continued until Durand and Lesley built and tested a full-scale prototype. Vincenti explains how they used laws of similitude and dimensional analysis to proceed from the data obtained on the forty-eight small-scale prototypes to the construction and testing of small-scale models and fullscale prototypes.[15] Once the full-scale prototypes successfully passed all necessary tests, the engineering research phase was followed by the manufacturing of propellers ready to be assembled into the aircrafts. Propellers only work in combination with the right engine and airframe, so new airplanes were designed with engines and airframes adequate to the selected propeller. In this way, the vast amount data provided by Durand and Lesley using experimental parameter variation became crucial for the design of new superior aircrafts, which had been the ultimate aim of the research.

Their work set a new standard in engineering research and design. Their case demonstrates the essential role experimental parameter variation plays in engineering research and the limits of theoretical knowledge, in this case the

[15] *Ibid.*, pp. 159-166.

blade element theory. Within a short period experimental parameter variation spread and became an established method that encompassed the early work from William Durand in the United States, Robert E. Froude in Britain, and Karl Schaffran in Germany.[16]

4. THE ENGINEERING OF THE FCC AUCTION

The philosopher Francesco Guala characterises the FCC auction as a case of economic engineering. He is mainly concerned with the problem of external validity. In particular, he is concerned with the kind of inferences which extend internally valid propositional knowledge produced in the laboratory into the outside world. The problem is philosophically relevant because those true and reliable inferences made predicting and explaining behaviour in the laboratory are not obviously true and reliable when new markets and state institutions are to be built. He argues that the combination of inferences by analogy, eliminative inferences and the reproduction of real world conditions in the laboratory explain the success of the FCC auction.[17]

While the propositional knowledge engineers have is certainly essential, the practical knowledge they have for the construction of social machines seems

[16] *Ibid.*, p. 294; see also D. W. Taylor (1924).
[17] F. Guala (2005), pp. 184-202.

to be more distinctive of engineering. Such a practical knowledge from engineering actually starts in the laboratory, where new mechanisms are tested. I argue that experimental parameter variation is an example of this practical knowledge. Guala himself is aware of the existing gap in the philosophical research on this kind of knowledge, which actually explains how while new markets and state institutions are built. He acknowledges this in the replies he gives to Anna Alexandrova and Frank Hindriks.

Alexandrova and Hindriks are both critical of the explanation Guala provides on the role experiments have in producing knowledge which lies outside theories and blueprints. They actually do not use the term 'blueprints', they use the term 'models' instead. Alexandrova is mainly concerned with the limitations blueprints have on the behaviour and other relevant conditions to be found in the outside world; when a new kind of auction is implemented; she explains that when 'economic models and experiments are used for engineering institutions such as spectrum auctions […] sometimes it is simply not known whether or not some assumption essential for deriving a particular effect in the model can be satisfied by the target system economists are constructing.'[18] Hindriks makes a general criticism to theoretical economists who are sceptical or neglect the contributions experimental economists could make creating new knowledge, and he criticises Guala for not making wider and stronger case in favour of

[18] A. Alexandrova (2008), pp. 199-200.

[262] F. Hindricks (2008), p. 217.

experimental economics beyond inference and external validity. He explains that 'except for a few scattered remarks, however, Guala does not directly address the scepticism that economists display about experiments.'[262]

In his reply, Guala highlights the good job experimental economists do testing the hypotheses contained in the blueprints, while at the same time recognises that 'the story is very different for experiments that are closer to application ('testbed' experiments). Here Alexandrova is right –no standards account of modelling does a good job at explaining what is going on.'[19] In his reply to Hindriks he explains that 'as he correctly points out, MEE [Guala's book *Methodology of Experimental Economics*] is quite bold in making prescriptive claims about experimental inference but relatively modest the role of experimentation in economics as a whole.'[20]

My argument on experimental parameter variation as a method of experimental economics answers the concerns expressed by Alexandrova and Hindriks. The use of experimental parameter variation shows the distinctive contribution experimental economists make to the design and engineering in economics. Moreover, the scope of experimental parameter variation could be extended to experiments performed in other social sciences.

The blueprint submitted by Milgrom, Wilson and McAfee represented a good solution to important problems such as complementary values, perfect

[19] F. Guala (2008), p. 229.
[20] *Ibid.*, p. 227.

substitution and preference maximisation on package-bidding. Nonetheless, its implementation represented a great challenge, the joint functioning of the three main mechanisms looked too complicated. Mechanism design theorists were no able to create a reliable expectation on how it all would work. Besides the right functioning, there were also concerns on how to prevent collusion and cheating. Unlike the other kinds of auction such as the Dutch and English auctions, multiple-round simultaneous auctions had never been tried before.

Rules constitute a fundamental part of mechanisms, and it the case of the FCC auction blueprint 'the most important – and debated – rules concerned increments, withdrawals, eligibility, waivers and activity.'[21] The auction would not be continuous but split into rounds with no pre-fixed number of total rounds, that is, the rounds would continue until no offer is put forward, and the winner is satisfied with the licences she has purchased. To ensure a maximal satisfaction of preferences, withdrawals were an important part of the rules. It was also important to prevent unnecessary delays speeding up the action without prematurely terminating demand, so rules on bid increments and an eligibility based on a deposit were considered in the blueprint.

As part of the activity rules the eligibility of bidders was important because some of them may want to slow down the bidding process by following a 'wait and see' strategy. Such a delay could cause significant inefficiencies, and it would also increase the costs of the auction. Therefore, the eligibility of any

[21] F. Guala (2005), p. 175.

bidder would be subject to an initial deposit called ‘initial eligibility’, which would also set a limit to the number of markets the bidder could participate in. This rule of eligibility also prescribed the regular use of such a deposit by spending parts of it in each bid. A refusal to do this would affect the eligibility of the bidder by reducing the number of bids she could make in the next round. Neither game theory nor auction theory provide information on how long an auction with multiple rounds could last, so with the eligibility rule, the auctioneer would be able to speed up the auction by enforcing an early commitment from all bidders. This rule would also help identify bidders who lacked any real interest in acquiring the licences, which was a problem auctions in New Zealand and Australia faced where uninterested bidders caused significant delays.

Three key data were missing on these rules, which no theory or previous knowledge on mechanisms could provide information on, namely:

1) Optimal bid increment.
2) Estimate of the total number of rounds.
3) Length cycles produced when licences are sold back

Without reliable data on these three aspects, the efficiency and smooth running of the auction would be compromise, and its full implementation could actually fail. The FCC hired the economist Charles Plott and asked him to perform experiments on these and other aspects of the auction. Guala provides a rich description of the experiments performed by Plott, however he does not draw a systematic methodological lesson from it. This is also pointed out by Alexandrova.[22] Charles Plott also provides a detailed description of the experiments he and his team in Caltech performed calling them 'testbeds', which he defines as 'a simple working prototype of a process that is going to be employed in a complex environment. The creation of the prototype and the study of its operation provide a joining of theory, observation, and the practical aspects of implementation.'[23]

The idea of a 'working prototype' is insightful and it actually corresponds to the term used in engineering, however the definition on the whole is poor and uninformative for any scientist who would like to have a clear and simplified understanding of the crux of the method. There is no abstraction made from the descriptive details, which would enable any scientist to see in a simplified manner the nature and systemic side of those practices. This is why I argue that by extending the method experimental parameter variation to the design of the FCC auction, we draw and extend methodological lessons which otherwise would remain lost in the rich description provided. Let us recall that experimental parameter variation consists of determining via experimentation the optimal performance of materials, processes or devices by varying the parameters of their operation.

[22] *Ibid.*, p. 197.
[23] *Ibid.*, p. 607.

The most comprehensive report of the experimental practices performed in preparation for the implementation of the FCC auction is provided by Plott. However, parts of the report are insufficient for producing a richer and more detailed methodological description. Another problem is the small number of experiments he performed. Unlike Durand and Lesley, who carried out comprehensive tests of propellers with a great range of variation, Plott and his team only conducted a small number of experiments due to the deadline and time and budget constraints set by the FCC. He explains that 'pressures of time and money substantially limited the amounts of experimental data that could be collected', therefore 'the strategy was to select certain key aspects of the parameter/theory space and collect such data as one could.'[24] Only two parameters were subject to variation, namely the total number of licences and the number of those with complementary values. In one case, seven licences were auctioned with two collections of three licences each having complimentary values; in the second case nine licences were auctioned with all of them having complimentary values. The experiments had two aims. The first one was to compare the efficiency of the multiple-round simultaneous auction allocating licences to bidders who value them most against a Japanese auction. The second one was to provide information on optimal and estimate values of the activity rules from the multiple-round simultaneous auction.

[24] *Ibid*. p. 614.

(1) *Optimal bid increment*. As an auctioneer, the FCC had an interest in identifying the winners rapidly, so that the auction could finish as soon as possible without negatively affecting the demand. For this purpose, the blueprint considered a bid increment every round. The auctioneer would do this by identifying the highest standing bid at the end of each round introducing an increment for the minimal bid in the next round. On the one hand, an excessive increment could deter potential bidders, causing demand-killing and the reduction of eligibility. On the other hand, a too small of an increment would not speed up the auction enough. Therefore, the discovery of the optimal increment became an important problem of design.

During the variation of increments performed the laboratory, Plott and his team observed that large increments above the highest standing bid effectively eliminated bidders too quickly placing at risk the inefficient allocation of licences. Without specifying the number and values of the variations, Plott explains that 'experiments had also produced evidence of the capacity of large increments to be demand-killing: A bidder failing to bid because of a large increment could lose eligibility.'[25] The FCC reports that an increment of ten to twenty percent above the highest standing bid was found to be the optimal

[25] *Ibid*., p. 633.

range.[26] This was enough to speed up the auction but not too big to cause demand-killing and inefficiency.

(2) *Estimate of the total number of rounds*. The second data to be obtained was an estimate on the total number of rounds. The FCC was concerned about the operation costs if the auction extended for a long time. Plott considered different aspects of the behaviour from the bidders and the auctioneer, which could compromise the efficiency of the auction. On the one hand, there was the strategic interest bidders may have in slowing down the auction. On the other, too much pressure on the bidders could also lead to overbidding. A further concern emerged from the allowance the blueprint made for the bidders to have time off for revising their strategies and budgets; the rule prescribed a stop after a number of rounds starting again the next day. This rule also helps prevent the winner's curse saving the FCC from expensive mistakes by preventing a legal case in court. Milgrom explained the case noting that 'sales of major companies take a long time. There are billions of dollars at stake here, and there is no reason to rush it when we are talking about permanently affecting the structure of a new industry.'[271] Therefore, getting an estimate of the total number of rounds and intervals became crucial data of design with important political, economic and legal implications.

[26] 'Smoothing Methodology Fact Sheet, 31th March 2003, FCC Experiments, Papers & Studies, electronic source: http://wireless.fcc.gov/auctions/default.htm?job=papers_studies [271] P. Milgrom (1994), p.11.

Hence, time between rounds would allow bidders to put forward more sensible bids, and it would also help prevent overbidding. At the same time, it was also important to reduce the number of rounds and intervals as much as possible to save on operation costs. In the experiments performed, Plott observed that the total time of the auction was mainly dependent on the number of rounds, rather on the intervals between them. He explains that 'many of the early experiments that were allowed to terminate naturally involved continuous-time processes without stages. Examination of these data suggested that the FCC auction could go through as many as a hundred rounds. The more rapid the rounds, the sooner would be the termination.'[27] This estimate of a hundred rounds was good enough because it allowed the FCC to calculate the operation costs and consider the need for an adjustment on the activity rules.

(3) *Length of cycles*. The Milgrom-Wilson-McAfee blueprint also included a rule allowing withdrawals because the winner decided that the price was too high, or because she just changed her preferences. The rule established that licences could be sold back to the market but the bidder returning them would have to pay the price difference, if the final price was lower than her own bid. Theoretically, it was expected that withdrawals could lead to 'cycles' where licences returned to auctioneer would have to be sent back to the market more than once, until one of the bidders becomes satisfied with the price. Although

[27] Plott, 1997, p. 633.

this possibility was envisaged, there was no way to calculate how long cycles might be.

Therefore, the production of experimental data on the occurrence and length of cycles was another important task which, along with the estimate of the total number of rounds, was relevant for estimating the total time of the auction. Too many cycles might significantly delay the termination of the auction, or even prevent the auction from ending. The experiments showed that a licence package may be released up to three times with the last holder losing money. Plott reported that 'since the new price of the item is above the average value of the marginal person, the new holder lost money. Panel B shows that releases can occur more than once during an auction. As can be seen in that experiment, the item was released two times, leading to a cycle of length three.[28] Hence, cycles were short but overpricing was likely to occur.

These data on cycles and those on bid increments and the total number of rounds were crucial for the final design and implementation of the FCC auction, which presumably led to an efficient allocation of telecommunication licences.[29] The revenue from the first round with nine auctions run between 1994 and 1996 was of twenty-three billion dollars, a large amount that has been hailed as a proof of the efficiency of the auction, and the power of game theory for design. However, the same credit should be given to experimental economists whose

[28] *Ibid.*, p. 625.
[29] The efficiency of the first round of FCC auctions has been a matter of controversy; see C. Plott (1997), p. 637; and P. Cramton (1997).

contribution was decisive for the final design and the successful implementation of the auction. The success of the FCC auction led governments in Europe to the implementation of auctions also for allocation of exploitation rights of the electromagnetic spectrum.[30]

In philosophy of science, design and engineering methods are often neglected by the excessive attention paid to theories and the methods associated to them. The use of theories for the design of blueprints has led some to argue that the success of the simultaneous ascending auction was due the advancement game theory and auction theory. While one can recognise the use of theories in both cases the fixed-pitch air propeller and the FCC auction, it would be a mistake to attribute the successful design and implementation of them exclusively to those

theories.

By reducing the explication of such success to the derivation of knowledge fromtheories, theory-testing experiments and externally valid interferences, philosophers of science are overlooking the distinctive features of experimental and engineering methods. My aim in this chapter has been to show the distinctive epistemic and methodological character of these practices and the knowledge they produce. Without a set of systematic practices producing data for design,

[30] See K. Binmore, and P. Klemperer (2002).

engineers and policy-makers would be left only with a set of abstract models and predictions on some tendencies.

Experimental parameter variation is a good example of practical knowledge which produces data theories cannot provide. It is also an example for philosophers and scientists on how to get a systematic and insightful interpretation of some of the practices performed by experimental social scientists, which otherwise would remain implicit or lost within long and detailed descriptions published in articles and books. Experimental parameter variation has a normative force analogous to any form of argument and inference studied in logic using rules such as *Modus Ponens*, a *Celarent* syllogism and Bayes' theorem. These rules provide instructions on how to perform inferences, experimental parameter variation provides rules on how to perform practices. Philosophers of science have excessively focused on inferential rules and propositional knowledge from theories and abstract models; by doing this they have overlooked and dismissed the role of scientific practices and the knowledge they produce. A comprehensive philosophy of design and engineering in the natural and the social sciences is needed. The subjects discussed and the arguments put forward in this dissertation are presented as an advance towards such a philosophy.

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