Centralized vs. Market-based and Decentralized Decision-Making: A Review of the Evidence in Computer Science and Economics

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April 2008

Abstract

Within both economics and computer science, many authors have claimed that decentralized or market-based approaches to decision-making are superior in general to centralized approaches. The contrary claim has also been made. Unfortunately, these claims are often supported only by informal or anecdotal evidence. In order to assess these competing claims, we present a review of the literatures in economics and in computer science bearing on these issues. Specifically, we report research findings based on empirical evidence and on simulation studies, and we outline the evidence based on formal deductive proofs or on informal and anecdotal evidence. Our main findings from this literature survey are: (i) for efficiency assessments, that there is wider variance in performance of organizations using Market-Based Control (MBC) than in organizations using Centralized Control (CC); (ii) that MBC and CC have the same efficiency on average; which may explain the observation (iii) that human and computer organizations tend to cycle between CC and Decentralized Control (DC) structures.

1 Introduction

"*Where facts are few, experts are many,*" Donald R. Gannon (`www.quotationspage.com/quotes/Donald_R._Gannon`)

A distributed computational system may be defined *"as one in which hardware or software components located at networked computers communicate and coordinate their actions only by passing messages. The motivation for constructing and using distributed systems stems from a desire to share resources"* [25, p. 2]. Several high-level and low-level issues arise when constructing such systems (e.g., networking, security, etc), but in this paper we focus only on the organization of these systems, and, in particular, the location of decision-making. Several different organizational structures have been proposed, which we will classify as Centralized Control (CC), Market-Based Control (MBC) and Decentralized Control (DC).

Miller and Drexler claimed in 1988 that *"market-style software systems are a fairly obvious idea [...] with (allegedly) great but unrealized potential"* [79, p. 162]. However, we may also find arguments stating that MBC is outperformed by CC or DC. In fact, *"the inherent features of centralization and decentralization are far from obvious"* [30, p. 193]. Despite the frequency of such claims, we know of no definitive method proposed to choose between these three forms of organization. But the selection of a specific organizational structure for a distributed computational system can have far-reaching and long-lasting consequences, and may be costly and difficult to alter once a computer system is in operation.

That this question is important to both computer science and to economics is shown by the fact that several researchers have considered the relative efficiency of CC, MBC and DC structures. In Computer Science (CS), Ygge [123] reports on simulation studies undertaken to compare MBC and CC structures, but he does not provide a good review of this literature; indeed, he even deplores the few comparatives studies of DC with other technologies.[1] Ygge believes MBC must prove its value to be widely adopted [124, p. 325]. In other work, Dias and his colleagues summarize what is known in theory and in practice about the quality of some MBC and DC systems (e.g., combinatorial auctions, central single task iterated auctions and peer-to-peer trading) in comparison with CC mechanisms used to coordinate teams of robots [31, Table 1]. Unfortunately, their review is short and limited to robotics. In Economics, textbooks provide formal models comparing CC and MBC, such as the chapters on Game Theory by Jehle [54] and the chapters on welfare economics and incentives by Mas-Colell [76]. Economists are also interested in empirical evidence, particularly at the macroeconomic level, as witnessed by the book by Ellman [33], in which Chapter 10 gives an overview on what is known about the relative advantages of capitalist and socialist structures of economic organization.

In this paper, we seek to present a literature review as wide as the one by Ellman [33] but in the area of Computer Science. Specifically, we summarize the previous reviews to present what is known about the relative advantages of CC, MBC and DC in Computer Science. For that purpose, we examine *empirical* and *simulation-based* evidence, and only outline *theoretical* and *informal* evidence. We do not develop the presentation of existing theoretical models because existing textbooks in mathematical economics undertake this task. We also present informal claims only cursorily because they are not often compelling, and because they tend to contradict one another, as noted by Devries [30]. Instead, our survey is intended to present all the facts obtained empirically or by simulation, along with an overview of theoretical and informal evidence, to achieve a complete overview of the evidence for and against these different organizational structures.

The structure of this survey is as follows. Section 2 describes the scope of this

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[1] Note that Ygge refers to DC as MultiAgent System (MAS) [122].

review, in particular defining what we call CC, and DC and MBC. Next, Section 3 presents the evaluation criteria which have been used within Economics and within Computer Science to compare and assess alternative organizational structures. These criteria will form the basis of our evaluations in the subsequent sections. Section 4 reviews the evidence we found in Computer Science (CS), and Section 5 that in Economics. Finally Section 6 ends the paper by summarizing the main results found in our survey of the literature.

2 Preliminary Methodological Remarks

In this Section, we first describe the types of evidence for scientific claims we consider, and then present our definitions of the three different types of organization structure.

2.1 Types of evidence

Essentially, we believe that evidence for scientific claims about real-world phenomena may be classified into one of four different types, as follows:

- *Deductive theoretical proof*: Real-world phenomena may often be represented by a formal model, usually articulated in a mathematical language. Such models may permit the formal derivation of properties of the model using deductive inference.[2] Following Euclid [35] and Hilbert [47], one common approach to deductive reasoning has involved *"specifying a set of axioms and the proof of the consequences that can be derived from those assumptions"* [6, p. 3]. This form of evidence for claims about real-world phenomena has become common within Economics, particularly since [3].
- *Simulation-based evidence*: Evidence of this type involves the results of simulation studies, using either computer simulation models or experimental simulation models, as described in [45]. This approach is between theoretical and empirical in the sense that, *"like deduction, it starts with a set of explicit assumptions. But unlike deduction, it does not prove theorems. Instead, [a simulation model] generates simulated data that can be analyzed inductively. Unlike typical induction, however, the simulated data come from a rigorously specified set of rules rather than direct measurement of the real world. Whereas the purpose of induction is to find patterns in data and that of induction is to find consequences of assumptions, the purpose of [simulation] is to aid intuition. [Simulation] is a way of doing thought experiments."* [6, p. 3-4]
- *Empirical evidence*: Empirical evidence is evidence collected from the real-world, but which is not the result of a simulation experiment, for instance, economic time series data of (say) historical stock market prices or of national inflation rates. This form of evidence is based on examples of particular phenomena,

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[2] Note that formal models, even mathematical models, are not necessarily articulated using some calculus or algebra of text symbols. Euclidean geometry and contemporary category theory, for instance, are two branches of pure mathematics which represent formal mathematical knowledge as diagrammatic images, and use graphical — i.e., non-text-symbolic — modes of reasoning over these images [40].

or phenomena having particular properties, and is used to support more general claims about the phenomena. Such reasoning is inductive, and has been formalized in statistical inference procedures, such as in the standard hypothesis testing procedures. [88]

- *Informal evidence*: Informal evidence for claims involve arguments which are not based on mathematical proofs, nor the results of simulation studies, nor empirical real-world evidence, but simply textual argument. The textual argument(s) presented for an informally-justified claim may depend on examples or anecdotes, or on further textual arguments. In Toulmin's influential model of argument [111], these informally-justified claims are thus typically *warranted* by further claims, for which no *backing* is presented, apart from further claims. Examples of informally-justified claims include: *"CC is more efficient than DC, because the central controller in a CC system finds the overall optimum rather than getting stuck at some local optimum,"* and, contrary-wise, *"DC is more efficient than CC because the agents in a DC system react faster to events in their environment than can a central controller."*

For perhaps most scientists, deductive arguments for claims are more compelling than any other form of justification. However, such arguments only compel those who accept the formal representation of the phenomena in question, the axioms assumed to hold, and the rules of inference used. All of these features may be contested.[3] The history of pure mathematics has seen many arguments over these features, for example the debate initiated by Brouwer's theory of intuitionism which rejected deductive inference procedures accepted by the majority of mathematicians [112]. Even deductive arguments within mathematical economics have been criticized for the rules of inference they use, e.g., the non-constructive methods, such as infinite choice sequences and arguments by contradiction, used in deductive proofs of the existence of market equilibria [115].

For many scientists, the results of simulation studies are usually less compelling as justifications for claims than are deductive arguments. Simulations continue to be undertaken, however, because realistic mathematical models of many complex phenomena are not analytically tractable; thus, simulation is the only way to acquire knowledge of the properties of the phenomena under study. Within Economics, there has been, until recently, a reluctance to publish simulation-based research: one study, for example, found only 8 out of 43,000 papers published in twenty leading economics journals involved simulation models [71]. Some of the reasons for this reluctance and its consequences are discussed in [75]. Simulation models, whether computer-based or not, are human artifacts, and thus the result of (explicit or implicit) design and implementation decisions. Empirical data also has an artifactual component, particularly in the social sciences. Even everyday economic variables and concepts, such as *Inflation* and *Gross Domestic Product* are man-made, and thus the result of design decisions made by economists, and operationalized by data-collection statisticians. Such decisions may encode particular implicit world-views, and thereby facilitate or inhibit

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[3] There is even evidence that acceptable rules of deductive inference may differ from one human society to another, e.g., [39, 104].

subsequent types of data analysis and comparisons. Environmentalists, for instance, have criticized the standard definitions of national income variables, such as Gross Domestic Product, for ignoring those economic activities and their effects which are not monetized, for example, pollution emissions or the loss of biodiversity. As will be seen below, empirical evidence has played a large role in macro-economics, in arguments about the best over-arching organizational structure for a national economy, as well as in discussions of economic policy.

The evaluation and acceptability of different forms of evidence is a much larger subject than we are able to cover here. Suffice to note that, within Economics, considerable attention has been given to the nature and acceptability of arguments for claims about economic phenomena: see, for example, [78] and [80]. Less attention has been paid to the question of the forms and acceptability of evidence within Computer Science, which may be a reflection of its relative youth as a discipline. In this paper, we focus our attention on simulation-based evidence and on empirical data, because deductive theoretical proofs are already well described in textbooks such as [54] and [76], and because informal claims tend to contradict one another, as Devries notes [30]. However, we do briefly outline these two forms of justification in order to provide insight into the empirical and simulation-based evidence which we focus our attention on.

2.2 Defining CC, MBC and DC

We now define precisely what we refer to as Centralized Control (CC), Market-Based Control (MBC) and Decentralized Control (DC). Our domain of application — whether a national economy or a computer system — is always assumed to be distributed. The organization which controls this distributed system may or may not be centralized; thus, centralization (or decentralization) is a property of the controlling organization, and not of the underlying system being controlled. We now define in detail these three forms of organization, firstly in CS, then in Economics.

2.2.1 Three types of organizations in CS

Following [29], we define a pure Centralized Control (CC) organization as a hierarchy with a single head at the top; that is, as an organization in which *"a central node has the entire responsibility for computing the optimal (or near optimal) solution/allocation to the problem"* [29, p. 2]. In contrast, we define pure Decentralized Control (DC) to be a flat organization in which control is *"distributed and concurrent"* [29, p. 2]. Davidsson and his colleagues also point out that other definitions may be possible, and that hybrid forms may be found between these two extremes.

We also consider the possibility of the Market-Based Control (MBC) of distributed systems because of the recent attention given to this model in computer science, e.g., [21, 23]. In MBC organizations, resources are allocated to distributed entities in the system through some system of payment by the entities, using either real money, or money-like tokens. These payments may be to (or through) some central entity, such as a clearing house or auctioneer, or they may be made bilaterally between the distributed entities involved in each transaction. One may therefore view an MBC organization as either centralized or decentralized. Even if there is a central auctioneer or clearing house, a market may be considered to be decentralized because decisions about resource allocation are being made by the distributed entities involved, with the central clearing house or auctioneer simply providing support for the execution of these decisions. Hence, MBC may be viewed as either a particular form of DC and a particular form of CC; since all the papers discussed in this review consider MBC to be a form of DC, we make the same assumption. Note that there are other forms of DC systems beside those using MBC: resources in a decentralized system may be allocated using non-monetary procedures, for example, procedures involving random allocation, or allocation via queues, such as on a first-in, first-out basis.

2.2.2 Three types of organizations in Economics

We now consider the definitions of the three forms of organization as seen from Economics. If we consider the economies of nations, then two principal kinds of economic organization are capitalism (i.e., DC, and, perhaps, MBC) and socialism (i.e., CC, and, perhaps, MBC in reference to "market socialism" [92]). Unfortunately, labeling an economy as of either kind is not always straightforward, as Pryor demonstrates by identifying three major analytical challenges [103, pp. 18–21]:

1. *The continuum problem*: Any criterion considered to define an economic system may not be manifest in a discrete way, but rather over a continuum. The problem is that some so-called socialist countries may practice capitalist methods, and vice versa. For example, the ratio of *"economically active population in enterprises and facilities owned by the government to total economy active"* was lower in socialist Yugoslavia in 1953 (30%) than in capitalist Austria in 1966 (31%) and in capitalist Finland in 1965 (34%) [102, Table 1-1]. In other words, real economies are mixtures of ideal capitalism and socialism.

2. *Discrepancies of meaning of system labels*: Several definitions of socialism and capitalism have been proposed, such as these by Pryor [103] (p. 20-1):

    - In capitalism the means of production are owned by private individuals or groups; in socialism the means of production are owned by the government or by social groups. The criterion here is the ownership of the means of production, as illustrated by the above example about Yugoslavia, Austria and Finland.
    - In capitalism the allocation of productive resources is unplanned by the central government and is coordinated through a market mechanism; in socialism the allocation of productive resources is planned by the central government and is centrally administered. The criterion here is the method of resource allocation.
    - In capitalism most consumer goods and services are bought by consumers and, further, governmental transfers of income are relatively small; in socialism more consumer goods and services are financed by the government through the tax system and allocated to consumers by non-market means

Market economies	Public consumption expenditures as percent of GNP	Centralized economies	Public consumption expenditures as percent of GNP
West Germany	30%	East Germany	33%
Austria	28%	Czechoslovakia	30%
Ireland	18%	Hungary	17%
Italy	28%	Poland	20%
Greece	20%	Bulgaria	22%
Unweighted average	24.8%	Unweighted average	24.4%

Table 1: Public consumption expenditures in western and eastern Europe in 1962 (summarized in [Pryor 1985, p. 25] from [Pryor 1968, p. 61]).

and, further, governmental transfers of income are relatively large. The criterion here is the relative importance of public consumption expenditure.

Differences exist even within what may be seen from a capitalist point of view as "the other system." For example, communism may be defined as the socialization of production and consumption, and socialism as the socialization of production facilities and the freedom of choice in consumption and in occupation [68, p. 9], but other definitions exist. Indeed, drawing a clear boundary between socialism and communism seems to be as difficult as drawing a boundary between capitalism and the pair socialism/communism. In the same spirit, Yugoslavia and Israeli kibbutzim are special cases of socialist organizations because they rely on self-management [33, p. 313].

3. *The coherence problem*: The problem with the three previous definitions of socialism and capitalism is that their differences refer to uncorrelated phenomena, that is, to phenomena that are not related and do not impact on each other. As a consequence, there is a lack of coherence. In order to illustrate this, let us focus on the third definition which relies on the relative importance of public consumption expenditure in the economy. Pryor [101, 103] presents the data reproduced in Table 1 in which every line contains a *"pair of nations with roughly the same per capita income"* (so that the *"causal factor underlying public consumption expenditures is held constant"* in every pair.) As can be seen in Table 1, the relative importance of public consumption expenditure is not a good criterion to define capitalism from socialism, since it does not allow separation of countries among these two systems. Pryor [103] gives additional examples to show that other criteria do not fare any better, and that using a combination of three criteria improves the classification but is still not perfect.

We have focussed here on the problem of how to define capitalism and socialism in economic terms [103, Chap. 1], but the same conclusion may also be drawn in political terms [103, Chap. 10]. In fact, it seems to us that the best definition of what a socialist country is be based on its *history*, that is, for example, whether a revolution has ever taken place to entrench socialism [14, p. 1116], but even this definition ignores cases such as the election of the marxist Salvador Allende Gossens as President of Chile, or the repeated re-elections of socialist parties in Scandinavia during the twentieth century.

Besides socialism and capitalism, some economists have also made a distinction between concentration and centralization of organizations, also referred to as horizontal and vertical dimensions of structure [113, p. 9-10]:

- "*Concentration and deconcentration are horizontal movements, i.e., consolidation or separation of agencies on the same hierarchical level. [...] In other words, horizontal relations are based on* equality *of power of the agencies and persons"* on the same hierarchical level. For instance, merging two entities on the same hierarchical level is concentration.
- "*Centralization and decentralization are vertical movements, i.e., consolidation of agencies on a higher hierarchical level and the separation of agencies at a lower hierarchical level respectively. [...] In other words, [vertical] relations are based on* inequality *of power"* of the agencies and persons on different hierarchical levels. For instance, merging an entity with another at a lower hierarchical level is centralization.

As a consequence of these concentration/horizontal and centralization/vertical movements, van den Doel [ibid., p. 10] reports that German authors as Eucken, Hayek and Röpke distinguished two ideal types of main forms of economic order:

- *Centrally planned economy*: This *"is an ideal type of vertical organization in which the economic actions in an economy are determined by the plan of one agency or individual."*
- *Exchange economy*: This *"is a type of horizontal organization in which all agencies or individuals make separate plans which they coordinate by a process of exchange."*

The first type corresponds to CC, and the second to both MBC and DC. We believe that these concentration/horizontal and centralisation/vertical movements can be used in a way that also allows us to distinguish MBC from DC, as shown in Table 2:

- *Hierarchical*: CC organizations have a single center at their head. That is, there is maximum centralization and minimum concentration, which corresponds to optimization in algorithmics and to mainframe architectures in Information Technology.

Organisation		Concentration	Centralisation	Examples of equivalents in CS
CC	Hierarchical	Low	High	Optimisation/mainframe
MBC	Markets	Average	Average	Services/Client-server
DC	Discussion	High	Low	Peer-to-Peer (P2P)/MAS

Table 2: The three types of organizations compared in this review.

- *Market*: MBC organizations have several centers, namely the market places in which the agents meet and trade with each other. As a result, both centralization and concentration are average, as happens in the notions of services and client/server architectures in computer systems.

- *Discussion*: DC organizations have no centers, or, more precisely, every agent is a center. In other words, this can be described as minimum centralization and maximum concentration, as in P2P and MultiAgent System (MAS) in CS.

Note that the labels "hierarchical", "discussion" and "market-based" are the names used in the Economics literature which compares these three basic methods of resource allocation, each one having specific advantages and disadvantages [33, p. 309]. Other classifications of organizations exist, but we will not use them since they do not overlap with DC, MBC and CC.[4]

Similarly, it is also possible to have classifications with more than three classes. For instance, Frayret [38] detailed further the triple {DC, MBC, CC} by studying the coordination mechanisms for manufacturing units, as depicted in Figure 1. This figure shows how the interdependency of one activity on another (externality) may be dealt with. We can recognize our three kinds of organizations: *"Coercive"* mechanisms correspond to CC/hierarchies, *"mediation"* may be seen as the use of a market (in which the mediator is the auctioneer), hence as a general case of MBC, and *"mutual adjustment"* is another expression for DC/discussion. This figure shows that all three types of organizations considered in this paper may be broken into smaller classes which are still very generic (e.g., both A-1 and A-4 are instances of CC).

2.3 Computational Economics (CE) and Agent-based Computational Economics (ACE)

Because we focus on the literature in both Economics and CS, we consider it necessary to discuss the work of the Computational Economics (CE) field, which overlaps both disciplines. As a result of this overlapping, this field most often produces what we name *"simulation-based evidence."* In fact, Amman [1] defines Computational Economics (CE) as *"a methodology for solving economic problems with the help of computing machinery."* This definition implies that CE may be applied in any branch of Economics, such as growth theory, macroeconomics, financial planning, game theory, etc. [59]. One of the subfields of CE provides several papers for this survey. This subfield is Agent-based Computational Economics (ACE), which is the part of CE using *"computational agent-based models [in order to] stress interactions, and learning dynamics in groups of traders learning about the relations between prices and market information"* in the context of finance, or learning about their environment in the general case [70, p. 680].

The WALRAS system [121, 18] may be the most famous system in the Agent-based Computational Economics (ACE) subfield. This system is also an example of

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[4] For example, Gough [43] classifies organizations depending on their dominant organizing principle, viz. the market, the state, and the community. Such a classification enables the definition of capitalism, socialism and communitarianism.

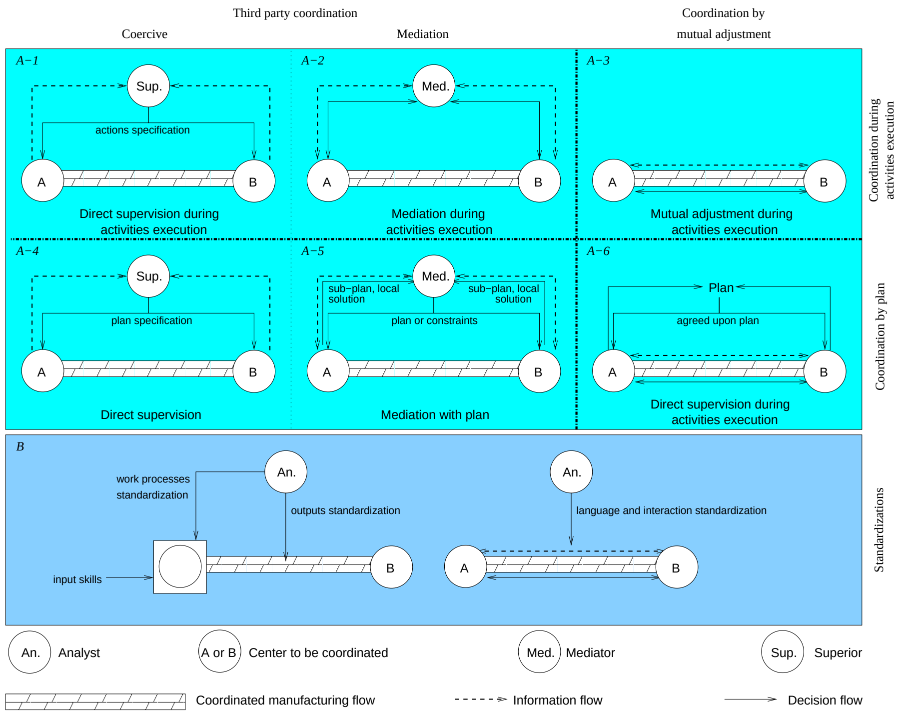

Figure 1: General classes of coordination mechanisms proposed by Frayret [2002].

what its author [121, p. 74] calls *"Market-Oriented Programming,"* even if the system is quite different from an actual market. In fact, WALRAS *"achieves price equilibrium and optimization in a rather unmarketlike manner, [because this system] requires each agent to submit an entire demand curve [see [121, p. 80]], then uses a central auctioneer [see [18, p. 8]] to sort things out until convergence to price equilibrium is achieved based on these demand curves. While the* tâtonnement *process is much in the spirit of the real [Léon] Walras in his general equilibrium formulation, real markets are not run by central auctioneers"* [61, p. 14]. Of course, we may object here that financial markets are both real and usually run by auctioneers, but Kroll's second argument about the fact that auctioneers do not receive demand curves but only prices still holds.

3 Evaluation Criteria

We now consider the metrics used in Economics and those used in CS to assess and compare organizations. Our presentation is based on the literature review in [33, chap. 10] which uses seven criteria "derived from the Marxist critique of capitalism" (ibid., p. 298) to compare socialist and capitalist economies. These criteria are summarized in Table 3. As can be seen in this table, most criteria are common to Economics and CS, e.g., most criteria measuring efficiency such as the social welfare, but there are a few exceptions, e.g., the guarantee an algorithm will succeed has no equivalent in Economics. The left-hand column of Table 3 summarizes the seven economic criteria in [33, chap. 10], the central column refines these criteria, and the right-hand column of the table suggests metrics which may be used to assess the performance of distributed computational systems.

We now detail the right-hand column of Table 3:

1. *Efficiency*: Static efficiency is the most used criterion both in Economics and CS. [77] details it as follows:

   - *Social Welfare*: The social welfare "expresses society's judgments on how individual utilities have to be compared to produce an ordering of possible social outcomes" [76, p. 117]. Aggregating individual utilities into a measurement of social welfare is not an easy task. However, some definitions are used quite frequently, such as [19, p. 17]:
     - *Utilitarian social welfare*: $\sum_i u_i$ considers that the utility of the group of agents is equal to the sum of the utilities u_i of every agent i,
     - *Egalitarian social welfare*: $\min_i(u_i)$ assumes that the utility of the group is the one of its individual with the smallest utility,
     - *Nash product*: $\prod_i u_i$ both takes the overall utility and the equality of the distribution of utilities into account, and
     - *Elitist social welfare*: $\max_i(u_i)$ is useful in cooperative environments in which only one agent needs to perform well for the system to succeed.
   - *Pareto Efficiency*: An outcome is Pareto Efficient or Pareto Optimal when no improvement is possible, in the sense that any other outcome making some agent better off also makes at least one agent worse off [76, p. 117].
   - *Individual Rationality*: Every agent is better off to be ruled by the considered CC/MBC/DC mechanism, than not to follow such a mechanism.
   - *Stability*: No agent can manipulate the considered CC/MBC/DC mechanism.
   - *Computational Efficiency*: The minimum of computational resources is necessary to the CC/MBC/DC mechanism to achieve an outcome.
   - *Distribution and Communications Efficiency*: Distributed protocols are those with computational redundancy, i.e., they do not have a single point of failure. Communications efficiency refers to the communications overhead.

   The labels of these criteria are of [106].

   Jennings and colleagues [56] (Sec. 3) add another criterion to this list of desirable properties:

   - *Guaranteed Success*: A protocol has this property if it ensures that eventually agreement is certain to be achieved.

Economic criterion	Short description of the economic criterion	Equivalent criterion in Computer Science
1. Efficiency	Static efficiency:	Static efficiency:
	- gross domestic product	- ?
	- level of productivity	- ?
	- Pareto efficiency	- Pareto efficiency
	- social welfare	- social welfare
	- individual rationality	- individual rationality
	- stability	- stability
	- Gen. Equil. & Socialist Calculus	- computational efficiency
	- ?	- distrib. & comm. effic.
	- ?	- guaranteed success
	- is progress continuous?	- feasibility
	- is progress constant?	- monotonicity
	- ?	- convergence
	- ?	- all network metrics
	- ?	- standard-deviation
	- ?	- tractability
	Dynamic efficiency:	Dynamic efficiency:
	- economic growth	- adaptation/learning speed
2. Labour process	Pace of work	Agent/CPU usage
	Full employment	% of agents idle
	Security of employment	Destruction of unused agents
	Social security	Taxes
	Trade unions	Coalitions
	Industrial safety	System robustness
3. Division of labour	Technical division (e.g., Taylorism)	Specialisation of the agents
	Division rulers/ruled (e.g., self-management or hierarchy)	Organisation of the agents (CC, DC or MBC)
4. Democracy and the state	Definition of democracy (liberal vs. totalitarian)	?
5. Distribution	How equally is the income/power shared?	How equally is the income/power shared?
6. Social ownership of the means of production	Difference between state and social ownerships	?
7. Economic planning	Where are markets used?	Where are markets used?

Table 3: Some possible criteria to assess organizations in Economics and CS (based on Ellman [1989]).

Kurose and Simha [65] suggest a few more criteria:

- *Optimality*: Does the CC/MBC/DC mechanism find the optimum of the systemwide utility function? Indeed, this criterion is very similar to social welfare, as will be seen in Subsection 4.2 when outlining the formal comparisons of MBC and CC.
- *Feasibility*: Does the CC/MBC/DC mechanism find a feasible allocation after each iteration, or, on the contrary, is only the final iteration sure to be feasible?
- *Monotonicity*: Does every iteration of the CC/MBC/DC mechanism find an allocation with a better systemwide utility than the previous iteration?
- *Convergence*: Does the CC/MBC/DC mechanism eventually always find an outcome?

Finally, we have found the following measures of efficiency proposed by various authors:

- *Network metrics*: We summarize here the metrics used to evaluate the routing in networks, including delay, packet loss, delay jitter and bandwidth [24, p. 616].
- *Standard-deviation*: [22] and [124] observe how widely the value to control (temperature) fluctuates around its average level. Similarly, this can also measure the balance of load among agents in order to evaluate task and/or resource allocation [124, 119, p. 110].
- *Tractability*: Are (economic or computer) decisions computationally tractable? We will see in Subsection 5.2 that the task of computing the General Equilibrium of a marketplace, or the Socialist Calculus of a Central Board Planner, are sometimes thought to be intractable problems in practice. In addition, Vellupillai has recently demonstrated that the extant proofs for claims of the existence of equilibria in the formal economies studied in mathematical economics rely on non-constructive mathematics [115].

All these metrics measure static efficiency, but dynamic efficiency may also be interesting. Dynamic here can be understood as how fast a system adapts itself to changes in its environment, possibly by learning.

Apart from efficiency, the other criteria in Table 3 are much less often used, and, therefore, less developed here. For example, the increase of efficiency corresponds to economic growth in Economics and to the adaptation of a system in CS. The other criteria in Table 3 are as follows:

2. *Labor process*: This family of criteria proposed by Ellman [33] translates into CS as (i) the load of agent or CPU usage, (ii) the ratio of agents idle, (iii) the question of removing non-useful agents from the system, (iv) the fact that money transfers (taxes) flows from wealthy to poor agents, for instance, in order to avoid the Prisoner's Dilemma (PD), (v) the existence or not of coalitions of agents, and (vi) the robustness of the entire system.

3. *Division of labor*: What Ellman [33] calls "division of labor" may be split in CS into (i) whether the agents are specialized on their tasks or not, and (ii) how the system is organized, viz. CC, DC and MBC.
4. *Democracy and the state*: Ellman [33] discusses here of the differences between liberal and totalitarian democracies. We do not see how this criterion applies to CS, apart from the problem shared with Economics of defining social welfare from individual preferences (see above about "efficiency").
5. *Distribution*: The distributions of income and power in the population seems to apply to CS as in Economics as the use of standard deviation suggested above.
6. *Social ownership of the means of production*: This is a discussion about the difference between state and social ownership of the means of production, distribution and exchange. We do not see has such a discussion may apply to CS.
7. *Economic planning*: This is a discussion about the topology of economic systems, that is, whether markets/MBC are used instead of some administrative/CC methods? Such a discussion may apply to CS but does not provide us with a metric.

Using these various assessment criteria, we next review the Computer Science literature and then the Economics literature comparing centralized with decentralized and market-based control structures.

4 Evidence from Computer Science

Section 2 above defined the scope of this paper as a review of mostly simulation-based and empirical comparisons of CC with DC/MBC systems, while Section 3 listed the possible criteria proposed for such comparisons. In this section we present a review of such comparisons from the literature of Computer Science, beginning with an overview of our findings.

4.1 Overview of the findings in the CS literature

Table 4 summarizes our findings reviewing the CS literature. The labels in columns 2, 3 and 4 of this table are not intended to be mutually exclusive but are presented to facilitate ready understanding. We now present the detailed findings underlying Table 4, with successive subsections dealing with (respectively): theoretical proofs; simulation studies; empirical data; and informal claims.

4.2 Theoretical proofs in Computer Science

We now summarize theoretical analyses comparing different structures, in operations research and in market-based computational systems. As mentioned earlier, we do not present the details of these theoretical comparisons; interested readers are advised to consult the works referenced here.

Topic and reference	Type of evidence	Result	Type of comparison
Relation of CC			
- *with DC*:			
. [95]	Formal	Review of decomposition methods.	CC/DC
. [27]	Formal	Example of decomposition method.	CC/DC
- *with MBC*:			
. [11]	Empirical	Example of decentralization of an auctioneer.	MBC/DC
. [58]	Formal	Discussion optimization vs. markets.	CC/MBC
. [123, chap. 3]	Formal	Example of maximization problem compared with example of market.	CC/MBC
Smart markets			
- *Computer networks and P2P*:			
. [49]	Formal	Payment scheme avoiding free riders.	MBC
. [17, sec. 3]	Simulation	Cost splitting of shared resources.	DC
. [17, sec. 6]	Empirical	Cost splitting of shared resources.	DC
- *Distributed control*:			
. [16]	Empirical	Policy to switch on/off web servers saves 29%-79% of electricity.	CC/MBC
. [108]	Empirical	1) Replace PID controllers by auction. 2) Auction more energy-efficient.	DC/MBC
. [123, 8.1-8.5], & [124, 1-8]	Simulation	1) Reproduce [108]. 2) Improve market and PID controller.	DC/MBC
. [123, 8.6], & [124, 9]	Formal	3) Propose efficient MBC-like controller.	DC/MBC
Supply chain management:			
- [29]	Simulation	Merger of CC and DC algorithms.	CC/DC
- [2] [94]	Empirical	P&G supply chain saves USD300 million annually for 1% this investment.	CC/DC
Information system architectures:			
- [60]	Informal	Cycles of centr./decentralization.	CC/DC
- [107]	Informal	Decision tree to choose CC or DC.	CC/DC
- [89]	Simulation	CC$\approx$DC.	CC/DC
- [96]	Empirical	Cycles of centr./decentralization.	CC/DC

Table 4: An overview of the diversity of comparisons carried out in CS.

4.2.1 Decomposition of mathematical programs

First, the field of operations research has developed methods to distribute the task of optimizing a centralized mathematical program. Palomar and Chiang [95] (p. 1442) describe the general idea of these approaches as the decomposition of the initial problem into subproblems coordinated by a high-level master program. Since these distributed algorithms find the global optimum of a problem, the solutions they find are as effective as the solutions computed by centralized algorithms, even though they may require more or fewer resources or time to complete. For example, Dantzig and Wolfe [27] proposed an algorithm that decomposes any linear program into several smaller linear programs, then iteratively solves these subproblems with a generalization of the simplex method, in order to solve the initial problem.

Next, most techniques can be called either primal decompositions that correspond to direct resource allocation, or dual decompositions that correspond to resource allocation via pricing [95, p. 1442]. This is similar to the two basic microeconomic approaches [65, p. 706]:

- *Price-directed* approaches first make an initial allocation and choose an arbitrary set of systemwide initial prices. Next, prices are *"iteratively changed to accommodate the 'demands' for resources [or tasks] until the total demand for a resource [or a task] exactly equals the total amount available, at which point the resulting allocation of resources [or tasks] is probably Pareto optimal."* Kurose and Simha (ibid., p. 706) see several drawbacks in this approach, for example, *"the fact that the pricing process must converge before resources can be allocated, a nontrivial constrained optimization problem must be solved by each economic agent at each iteration, and finally, only a weakly (Pareto) optimal allocation of resources is obtained."*
- *Resource-directed* approaches make *"each agent compute the marginal value of each resource [or task] it requires given its current allocation of resources [or tasks] (i.e., compute the partial derivative of its utility function (performance) with respect to that resource, evaluated at the current allocation level). These marginal values are then sent to other agents requiring use of this resource [or task]. The 'allocation' of the resource is then changed such that agents with an above average marginal utility receive more of this resource and agents with a below average marginal utility are 'allocated' less of the resource."*

4.2.2 Markets vs. optimization

Concerning the comparison of MBC with CC approaches, Carlsson and colleagues [15] note that equilibrium markets attempt to maximize the match between supply and demand; this matching process can be understood as the marketplace optimizing something. Karlsson and colleagues [58] summarize several examples of use of markets to find the optimum solution to a problem.[5] We present here how Fredrik Ygge [123] investigated formally the relation between market mechanisms and optimization. First of all, Ygge and Akkermans [124] (p. 303) give the references of the earlier work on

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[5] Note that Per Carlsson is a co-author of the first paper and Maria Karlsson of the second one.

which is built what follows. Let us focus first on the chapter 3 of the PhD thesis of Ygge [123] in which he compares some maximization problem MP with some market M. He then proves that *"any Pareto-optimal allocation in* M *is a solution to* MP*,"* and *"if there exists a competitive equilibrium in* M *then this is a solution to* MP*."* (Recall we said in Section 3 that optimality would be shown to be close to social welfare here.) Next, he defines some MP' in the same way as MP except that the problem is to maximize the expected value instead of the actual value of the sum of functions, and some market M' is similarly a transformation of M in which expected utility is considered instead of actual utility. The same two aforementioned properties are proved, that is, *"any Pareto-optimal allocation in* M' *is a solution to* MP'*,"* and *"if there exists a competitive equilibrium in* M' *then this is a solution to* MP'*."*

Let us now turn our attention to a similar work by Tan and Harker [110] who propose a model to understand the circumstances favoring either CC or MBC scheduling. Their model is much more detailed than Ygge's, and allows them to show that *"distributed scheduling methods work well for systems where information technology is inexpensive relative to production cost, processing times are relatively long, and where the number of agents in the system is not too large."*

4.2.3 Smart markets

Smart markets can be defined as *"mechanisms [that] combine a computer network that collects bids from agents with a central computer that selects a schedule of bids to fill based upon maximization of revenue or trading surplus"* [11, p. 41]. The study of such markets may be carried out formally in order to study [73, Subsect. 3.2]: efficient network traffic routing [4, 57], CPU allocation [90], incentives in peer-to-peer systems [49], etc.

For example, several economic models of networks have been proposed in order to prove various properties in these systems, such as the efficiency of information routing or the diversity of content offered by a Peer-to-Peer network. This second metric was considered by Huberman and Wu [49], who used it to assess the incentive mechanism they propose. This mechanism relies on a market to motivate buyers and sellers of files in a way that the demand for any file can be fulfilled by the system. As a result, the free rider problem is solved. Similar questions have also been addressed by simulation (e.g., [17, sec. 3]) or empirically (e.g., [17, sec. 6]), but we have not found any comparisons of such DC or MBC approaches with CC.

4.3 Simulation-based evidence in Computer Science

We now consider in detail the comparisons obtained by simulation studies. We successively present the work on distributed control, supply chain management, smart markets, and the architecture of information systems. Please recall that these labels do not intend to be mutually exclusive, but only to assist the reader in understanding the material surveyed.

4.3.1 Distributed control

We have already spoken of Fredrik Ygge in the theoretical comparisons in Subsection 4.2. He also undertook interesting comparisons with simulation. Precisely, [124] extended by simulation the initial system of Clearwater and colleagues [22] which was tested empirically. We shall see in Subsection 4.4 the results obtained by [22] in their comparison of a market with the traditional technology in order to manage a building Heating-Ventilation-Air Conditioning (HVAC) system. To this end, Clearwater and his colleagues compare a setting with one conventional Proportional-Integral-Derivative (PID) controller per office, with a setting with one agent bidding to buy or sell fresh air in every office. The second setting is an auction in which the successful buyers open their air damper in order to receive the cold air put in the duct work by the successful sellers. According to these authors, this example of climate control reminds us of the fact that many applications in which MultiAgent System (MAS) have recently been successful were close to control engineering [124, p. 301].

While [22] compared these two controllers with real buildings (and so discussed in more detail in Subsection 4.4 below), [124] compared them with a simulated building (see[6] Figure 3). Next, they also claim their own simulation was also independently recreated from their as well as Clearwater and Huberman's publications (ibid., p. 314). In addition to this confirmation of Clearwater and his colleagues' results, Ygge and Akkermans provide several new insights. In particular, both studies find that the standard deviation of the temperature in the offices is reduced by at least one order of magnitude by the market approach [124, p. 314]. They explain why the auction used by Clearwater *et al.* [22] (which they call *Market-A*) is more efficient than traditional control-theoretic approaches — the auction allows all the agents to broadcast information, while the control-theoretic approach (which they name *Control-A*) on which the PID is based only relies on local information.

Ygge and Akkermans [124] next extended this work in order to: (i) understand why the market technique outperforms the conventional alternative; and (ii) find market-based and/or centralized approaches which are even better. With regard to the first point, they implemented *Market-A'* by modifying *Market-A* so that the auction is removed. This allowed them to understand the reason for which their, as well as Clearwater's, market, is better than the traditional PID approach. This reason lies in the communication between rooms, that is, every PID controller in *Control-A* works independently while the auctioneer in *Market-A* aggregates all the bids which depend on room temperatures. In other words, the work achieved in [22] is not a comparison of a CC or DC system with an MBC approach, but a comparison of a system without (*Control-A*) or with (*Market-A*) inter-room communication.

Next, *Market-A'* applies another aggregation of the temperature than the clearing price in *Market-A* by which the auctioneer in *Market-A'* lets every agent know the average temperature and the average setpoint temperature in every room, which allows *Market-A'* to perform ten times better than *Market-A* (ibid., p. 317-8).

Since the access to global data is very important, these authors next designed

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[6] [124] only reproduced the results in Figure 3 because the results of [22] reproduced in Table 8 are more delicate to simulate. In fact, costs depend on *"how the fan system is coupled to the office temperatures"* and on *"differences in geography, building construction, and facility management practices"* [22, p. 270-1].

Control-B as a conventional PID controller (as in *Control-A*) which incorporates global data. They found that *Control-B* performs as well as *Market-A'*, and, therefore, ten times better than the original *Market-A* proposed by [22]. In other words, if a traditional controller can access the same global information as the auction of [22], then this new controller is more efficient. In addition, controller *Control-B* is easier to understand since it relies on well-known methods and theories (ibid., p. 319-20).

Finally *Market-B* is constructed so that it is as efficient as *Control-B* while being decentralized. This last stage of the work is formal and should thus appear in Subsection 4.2. We should notice here that *Market-B* is not a real market because the agents have to submit a demand function to the auctioneer instead of a single demand (ibid., p. 321), working in the same way as the WALRAS system mentioned in Subsection 2.3 [121, 18].

Another paper from the project[7] of [124] also compares traditional technologies with new technologies to control building temperature. In fact, [28] empirically study energy savings and increased customer satisfaction with a system that automatically detects and identifies people in order to set rooms to their personal heat preferences. The four compared technologies are:

- *Thermostat* (basic traditional technology): The temperature in the offices and the meeting room is always set to 22 °C because the people are not assumed to lower the temperature when they go home.
- *Timer-based* (advanced traditional technology): A timer raises the temperature to 22 °C in all rooms from 7 a.m. to 7 p.m., then lowers it to 16 °C from 7 p.m. to 7 a.m.
- *Reactive MAS* (basic new technology): Any room in the building containing a person is set to 22 °C, otherwise to 16 °C. Similarly, the temperature of the meeting room is set to 16 °C when it is empty, otherwise to 22 °C.
- *Pro-active MultiAgent System* (advanced new technology): The rooms are heated to the preferred temperature of the people, as recorded in their Personal Digital Assistant (PDA). The systems sets this temperature in advance thanks to people's diary, also managed by their PDA.

Table 5 summarises the performance obtained by the simulation of these four approaches. As can be expected, the more "intelligent" an approach, the more energy-efficient and comfortable to the users. However, this work only compares CC approaches, and, more precisely, different levels of "intelligence" in CC approaches. In fact, the two approaches with MAS are not really DC in the sense that they do not involve any process of decision making (e.g., negotiation). In fact, agents are only a way to implement the fact that a thermostat-agent knows whether the person occupying its room is there or not and what her preferences are.

On the contrary, the following paper about supply chains, also written by Davidsson, is much more in the spirit of the content of this review.

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[7] Project Information Society Energy System (ISES), see: `www.enersearch.com/dwn_pub_project.html`.

4.3.2 Supply chain management

Davidsson and colleagues [29] wrote a very interesting paper comparing four approaches of planning and allocation of resources in a supply chain with two agents, viz. Agent A for production and production inventory planner, and Agent B for transportation and inventory planner. These four approaches are:

- *Pure agent* (DC): This decentralized approach lets Agents A and B apply rules in order to communicate and make decisions.

- *Embedded optimization* (hybrid CC/DC): This approach is a hybrid of the Pure agent and Embedded optimization approaches, that is, each agent optimizes the part of the problem she is concerned with.

- *Pure optimization* (CC): This centralized approach adds an Agent C that runs the Cplex[8] optimizer to make the decisions for both Agents A and B.

- *Tactical/operational* (hybrid CC/DC): This approach is another hybrid of centralized and decentralized. Here, an Agent C calculates a global plan as in *Pure optimization*, and this plan is next used by Agents A and B to improve the decisions made by the rules of *Pure agent*.

Table 6 summarizes the results obtained when the quality of the prediction of the demand is either rather good (Case 1) or low (Case 2). In terms of time and costs, we can see that the hybrid approach called *Embedded optimisation* is between the two pure approaches (except for its cost in Case 2), while *Tact./oper. hybrid* seems to be both more cost-efficient and less time-efficient than the two pure approaches.

Another application to supply chains was reported by Anthes [2] from a white paper of the Bios Group [94], which proposed agents to model a part of the supply chain of Procter & Gamble.[9] Conversely to the previous work of [29], this one does not compare DC with CC directly, but compares agent-based simulation with traditional technology in decision support systems. More precisely, simulation is used as a tool to help managers make decisions for their (real) company, so that we could also have presented this work in Subsection 4.4. Unfortunately, few details are provided, except a very good argument for agent technology. In fact, they claim saving USD 300 million

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[8] See `www.ilog.com`.

[9] See `www.pg.com`.

Control approach	Average weekly energy consumption (kW.h)	Average degree of temperature satisfaction (%)
Thermostat	221.8	100.0
Timer-based	154.3	91.8
Reactive MAS	136.2	97.7
Pro-active MAS	137.0	100.0

Table 5: Simulation results of four approaches of controlling lights and heating in an office building [Davidsson 2005].

Approach	Total cost – Case 1	Total cost – Case 2	Time (s)
Pure Agent	22.7	23.4	0.03
Embedded optimisation	21.7	22.7	0.07
Pure optimisation	20.7	25.3	0.22
Tact./oper. hybrid	20.2	21.4	0.44

Table 6: Simulation results of four approaches of supply chain management [Davidsson 2007].

annually for 1% of this investment. Apart from that, we do not know exactly what is compared with what, nor do we know if these savings are only due to the reengineering of processes rather than to the agent-based simulation.

In other work, we described [83] how we expect to use a CC supply chain as a benchmark to our MBC supply chain. Specifically, this latter supply chain is market-mediated in the sense that the companies at each level buy products in a double auction, then transform these products, and finally sell the transformed outputs in a second double auction. The behavior of this MBC supply chain is described in [84], and we are currently working on a CC controller to replace the auctioneers.

Finally, it is worth noting that Estelle and colleagues [34] used Empirical Game Theory in order to analyze the behavior of entrants in the Trading Agent Competition - Supply Chain Management (TAC-SCM)[10]; that is, they used Game Theory, a formal tool, in order to study simulation outcomes. We do not develop this idea here because this is not a comparison CC vs. MBC/DC, and we shall come back to Empirical Game Theory in Subsection 5.2.

4.3.3 Smart markets

We have already described smart markets as auctions run by a computer through a network. *Spawn* is such a smart market, being an MBC system for exploiting the idle time of networked computers. The system is tested by making it allocate concurrent Monte Carlo simulations as prototypical applications. The assessment metric used is the efficiency of the system at allocating Monte Carlo applications to be executed by otherwise idle computers. Waldspurger and colleagues [119] (p. 110) in Figure 3 compare the number of simulations calculated by *Spawn* with the ideal number of simulations that could be performed concurrently on independent machines. (We do not reproduce that figure here.) The results of this simulation indicate 0.9 Monte Carlo trials per second are executed by *Spawn*, while 1 Monte Carlo trial per second could have been ideally obtained by running independent serial Monte Carlo tasks on the same sets of machines.

Next, Ferguson *et al.* [37, 36] also worked on MBC techniques in order to assign tasks to processors. For that purpose, they compared the non-economic algorithm HOP 1 with the Hybrid and Sealed bid auctions. Figure 2 reproduces the results obtained with the simulation of a network of nine processors connected in a 3×3 mesh. As can be seen in this figure, the non-economic HOP 1 is as good as the Sealed bid economy

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[10] See `www.sics.se/tac`.

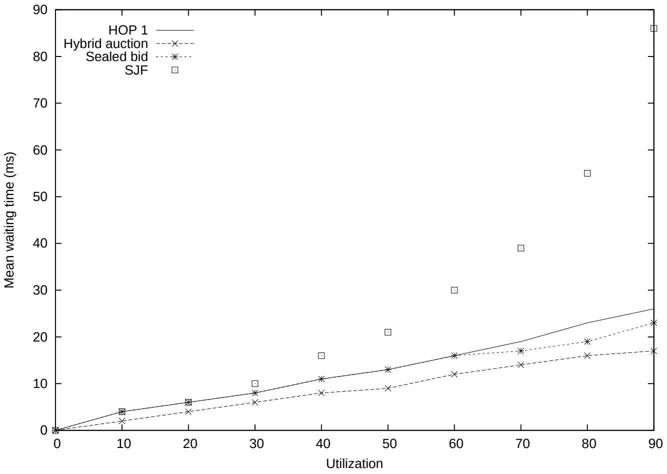

Figure 2: Mean job waiting time obtained with four allocation algorithms [Ferguson 1996, Fig. 1]; [Ferguson 1988, Fig. 7].

Component allocation strategy		Application partitioning			
		Centralized	Thin client	Fat client	Decentralized
Minimised data	Minimised Programs	2,104,610	2,104,610	2,561,330	2,459,130
	Localised Programs	2,511,190	2,511,190	2,503,750	2,459,130
Localised data	Minimised Programs	2,331,410	2,331,410	2,268,930	2,044,330
	Localised Programs	2,081,390	2,076,390	2,073,950	2,034,330

Table 7: Aggregate cost in [Nezlek et al. 1999, Table 3].

only at low utilization, but worse at high utilization. Next, the Hybrid auction is always better than HOP 1 and the Sealed bid. Finally, the dummy SJF (shortest job first) is the worst. As a consequence, the authors conclude that economic concepts are at least as good as traditional cooperative algorithms at balancing load. Unfortunately, they did not investigate the circumstances under which this holds in order to understand what makes the two auctions better than HOP 1.

4.3.4 Architecture of information systems

Nezlek and colleagues [89] simulated the costs of sixteen configurations of the computing architecture of a company. Specifically, they compared the four application partitionings (centralized, thin client, fat client, and decentralized) and four component allocation strategies (minimized/localized data and programs) presented in Table 7. The costs in [89, Table 3] are more detailed than our Table 7 because we have aggregated the constituents (acquisition/operating costs, and server/user/communication costs) of these costs. The conclusion drawn from these simulations is that *“the effect of component allocation strategies [CC or DC] are much greater than the effect of ap-*

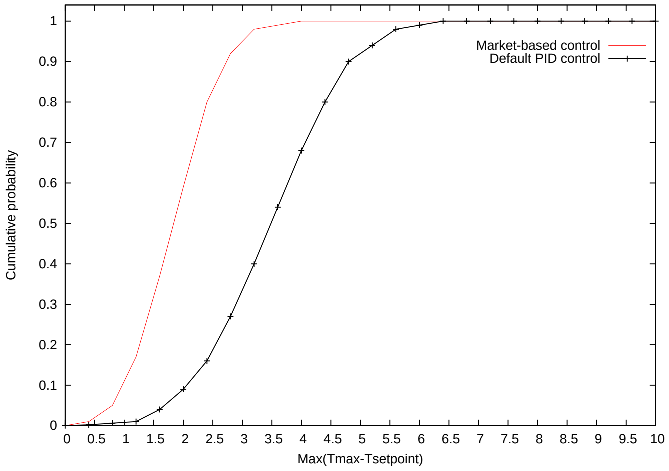

Figure 3: Cumulative probability distribution for the extreme deviation from setpoint temperature for all offices using the HVAC [Clearwater et al. 1996, p. 268].

plication partitioning." In other words, the decision of whether to centralize or not has little impact on the costs in this case study.

4.4 Empirical data in Computer Science

We now review the comparisons carried out empirically. We successively present the data on distributed control, smart markets, and computer system architectures.

4.4.1 Distributed Control

We outlined the work of Clearwater and colleagues [22] on the control of the Heating-Ventilation-Air Conditioning (HVAC) system of a building in Subsection 4.3 in order to introduce the research of Ygge and Akkermans [124] it inspired. While the latter use simulation, Clearwater *et al.* test in real-life their MBC controller with the traditional Proportional-Integral-Derivative (PID) technology. Specifically, they performed some experiments on the top floor of the three-story Xerox PARC (Palo Alto Reserch Center) building (ibid., p. 279). Figure 3 shows that the auction "reduces the temperature deviation from setpoint of the most out of tolerance office by about 2°F" (ibid., p. 268), which results in more comfort to the users of the building, thus to an increased productivity if these people are at work. Table 8 shows that the auction also saves energy, thus money. The data in this table present the ratio of traditional to market-based energy use for the fan of the HVAC. Values less than 1 mean that the market uses less energy. *"The first column is a reference area which does not run the auction but for which, for comparisons purposes, we can still compute the energy ratio for the same days as the areas that did use the auction"* so that this *"reference area provides a rough measure*

Auction Fan Energy / Conventional Fan Energy			
Outside Temperature Range (°F)	Reference	Auction (Area 1)	Auction (Area 2)
65-75	0.978 ± 0.015	0.985 ± 0.015	1.045 ± 0.010
75-85	0.973 ± 0.009	0.975 ± 0.008	1.010 ± 0.007
85-95	1.017 ± 0.011	0.958 ± 0.019	0.903 ± 0.015
95-105	1.002 ± 0.045	0.936 ± 0.029	0.929 ± 0.035

Table 8: Ratio of conventional to market-based management of energy use for the fan of the HVAC [Clearwater et al. 1996, p. 271].

of the magnitude of fluctuations to be expected, which are a couple of percent." Table 8 shows that energy savings increase with the outside temperature, i.e., the relative performance of the MBC with regard to the traditional PID controller is better when *"more thermal stress is placed on the building."* We recall here that [124] explained this good performance of the auction by the fact that MBC creates a communication link between rooms, while PID does not.

4.4.2 Smart markets

Chase and colleagues [16] also compared the energy used depending on the architecture of the control system, but in the context of web server hosting centers. Specifically, hosting centers have to turn on additional servers in order to face an increasing demand, and to turn off servers when less web pages are requested. With experiments on the web page of IBM[11] and of the 1998 World Cup, their MBC approach reduced energy usage by at least 29%-78%, depending on the considered experiment.

Next, Brewer [11] wrote a very insightful paper in which he proposed to use an auction called Computation Procuring Clock Auction (CPCA) in order to decentralize the optimization carried out by the auctioneer of another auction called Binary Conflict Ascending Price (BICAP):

- *Binary Conflict Ascending Price (BICAP)*: Brewer and Plott [12] proposed the BICAP smart auction in order for Sweden to change from a centralized railroad management system to a decentralized one. In their experiments, train companies are played by humans who bid for routes. The BICAP auctioneer needs to calculate a new schedule showing the effect of every new bid on the potential scheduling outcome. This calculation is the optimization of the schedule of trains that *"maximizes the bid revenue from [the] set of known bids relative to a known feasibility constraint"* [11, p. 43].

- *Computation Procuring Clock Auction (CPCA)*: Brewer [11] proposed CPCA in order to decentralize the optimization carried out by the BICAP auctioneer. The idea of CPCA is that every agent submits an improved solution in comparison with the best known solution to the optimization problem, and earns $\lambda\%$ of the

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[11] See `www.ibm.com`.

money saved by the auctioneer. CPCA has a clock making λ increase from 0% to 100%, and this clock is reset after every improved solution.

- *BICAP+CPCA*: In the merger of both auctions, agents bid in either auctions, that is, they bid on trains in BICAP and propose improved schedule in CPCA. CPCA is reset after every BICAP bid. There is still an auctioneer broadcasting the state of BICAP and CPCA, receiving bids and improved schedules, and paying the CPCA rewards, but this auctioneer does not need anymore to optimise anything. Hence, a part of the task of the auctioneer is decentralized to the agents, but the auctioneer remains as a center in the system.

We report this research in this section, because [12] assessed the efficiency of BICAP empirically with human subjects, as well as [11] did with BICAP+CPCA. The first reason this research is interesting is that it shows how to decentralize a previously centralized optimization process by letting agents iteratively propose improvements. The second reason is the fact that the efficiency of CPCA is compared with the optimum. In fact, one of the metrics used to evaluate BICAP+CPCA is the *"computing effectiveness,"* defined as the ratio of the quality of the best schedule found by CPCA over the highest possible value of this quality. The human subjects ran BICAP+CPCA over 13 periods, and this ratio always reached 1.0, meaning that CPCA found the optimum in all periods [11, Table 3]. Unfortunately, the BICAP+CPCA auctioneer has a few drawbacks, such as the fact that it cannot guarantee to find the optimal schedule, or that it seems to optimize more slowly than the BICAP auctioneer used by Brewer and Plott [12].

4.4.3 Mainframe vs. client-server architectures

We conclude this review of empirical evidence in CS with some studies of computer system architectures. Peak and Azadmanesh [96] analyzed the sales data of mainframes, minicomputers and microcomputers. This data was obtained from consulting companies such as Gartner Inc.[12] and synthesized into a figure reproduced here as Figure 4(a). Peak and Azadmanesh concluded that *"commercial computing [had] already experienced two centralization/decentralization cycles"* (ibid., p 303) and that computing was at the end of the second cycle, just before the start of the third cycle. The table in Figure 4(b) summarizes the conclusions drawn from Figure 4(a). The most obvious remark about Figure 4(b) is that the explosion in use of the Internet and the World-Wide-Web is not explicitly mentioned, even though it is easily inferred from the statements about the use after 1997 of desktop computers to access mainframe servers through networks. More recently, Gilder [41] confirmed this return to more centralized architectures with what he calls the *"information factories"* of companies such as Yahoo! and Google.[13]

Finally, Peak and Azadmanesh explained the cycles of centralization/decentralization in Figure 4(b) to be the consequence of technological advances. In this regard, Schuff and Saint Louis [107] also noted such cycles of centralized and decentralized

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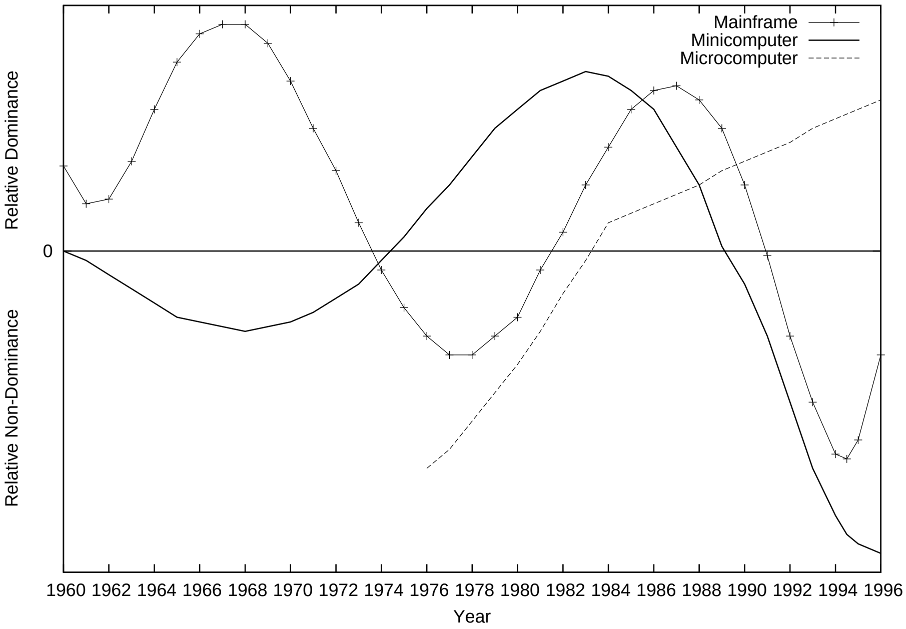
[12] See `www.gartner.com`.

[13] See `www.yahoo.com` and `www.google.com`.



(a) Combined mainframe, minicomputer and microcomputer modeled sales trends.

	Period	Year (approx.)	Major features	Reasons for change to the period
Cycle 1	Centralisation	1945-1978	Mainframe environment	Development of mainframe-related technology
	Decentralisation	1979-1984	Distributed data processing	Lower cost of minis; Better performance of minis
Cycle 2	Centralisation	1985-1989	Relational data bases	Lack of networking standards Limited computer networking Introduction of relational DBs
	Decentralisation	1990-1997	Client-server architectures	Corporate restructuring Growth of desktop computing Standardized networking and protocols User autonomy
Cycle 3	Hybrid centralisation	1997-?	- Support economies of scale - Mature uses of mainframes	Desktop computer - high cost of ownership Mainframe superservers (DB, etc.) Network management software

(b) Conclusions drawn from Figure 4(a).

Figure 4: Centralisation/decentralisation cycles [Peak and Azadmanesh 1997, p. 312 & 315].

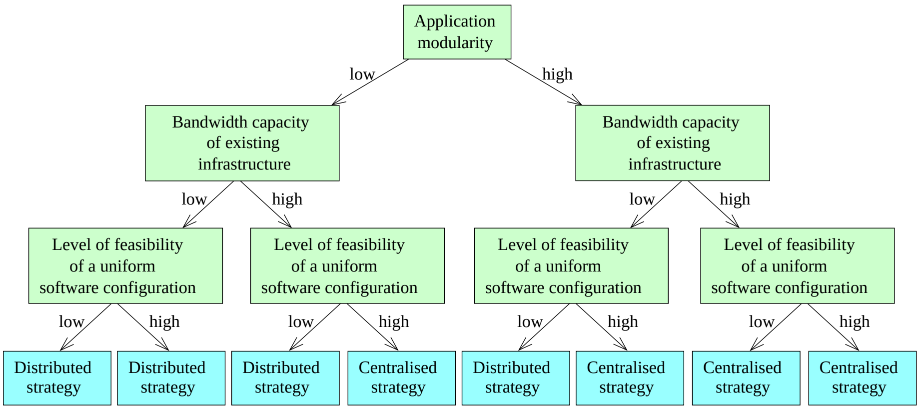


Figure 5: Decision tree to choose the best software configuration strategy [Schuff and Louis 2001, p. 93].

application software distribution, but they did not provide evidence supporting the existence of such cycles.

4.5 Informal Claims in Computer Science

We now conclude this section about the literature in CS with a discussion of informal claims. We do not aim to review all claims, but rather to give an overview of the different points of view used to address the debates DC vs. CC, then MBC vs. CC.

4.5.1 DC vs. CC

We concluded the previous subsection discussing Schuff and Saint Louis [107] who not only observe the cycles of centralization and decentralization of institutional information systems, but also propose the decision tree in Figure 5 to decide whether the configuration of a software should be centralized or not. In this figure, the three criteria used to choose between DC and CC are the application modularity, the bandwidth capacity of the existing architecture, and the level of feasibility of a uniform software configuration. We found this decision tree interesting because it clearly maps these three criteria onto the decision to decentralise or not. Unfortunately, this tree seems not to be build on any factual evidence, conversely to the aformentioned paper by Nezlek and colleagues [89].

In addition, other criteria may be found in the literature [10], [55, p. 5-10], [122, p. 225-6]. For example, Mullender [85, p. 7] proposed the following criteria to decide between a centralized and a decentralized system: (i) people are distributed, information is distributed; (ii) performance/cost; (iii) modularity; (iv) expandability; (v) availability; (vi) scalability; and (vii) reliability. Similarly, Coulouris and colleagues [25] (p. 44) proposed: (i) performance issues; (ii) quality of service (reliability, security and performance); (iii) use of caching and replication; and (iv) dependability issues.

Following [109] and [82], we propose to classify these criteria into two categories, namely hard and soft. *Hard criteria* are those required to make CC/DC feasible. For example, it is not possible to run in a CC-way a DC algorithm when some information is not accessible to the central decision maker of the CC organization (for example, because of confidentiality concerns) [11, Footnote 2]. As a consequence, information confidentiality is a hard criterion forbidding CC. On the other hand, *soft criteria* deal with the quality of the implemented system; that is, these criteria have an impact on the overall efficiency of the implemented system. For instance, information may be hardly accessible to a central decision maker because of its bulk (e.g., the network is not adapted to the flow of the transmission), in which case the system is less efficient because the decision maker has to wait for information. Information bulk is therefore a soft criterion making the use of CC less efficient, but still possible. The three criteria in Figure 5 are also examples of soft criteria because the answer to a single of them do not determine the use of either DC or CC. Of course, all hard criteria must be satisfied before checking soft criteria, since it would be useless to see, for example, that a CC approach to some problem would be more efficient than some DC one, while this CC is not feasible at all in practice. All the articles reviewed in this paper only consider soft criteria since we have not found any article saying, *"we use DC because CC is not possible for reasons X and Y."*

After that, the most interesting criteria are at the border of CS and Economics. In particular, we now quote Ygge [123, p. 37–38], who took the arguments of Kurose and Simha [65, p. 705]:

1. *"An inherent drawback in any non-distributed scheme is the one of reliability, since a single agent represents a critical point-of-failure in the system."*
2. *"The optimization problem itself might be an extremely complex task. A centralized approach towards optimization ignores the computational power inherent in the network itself and instead utilizes only the computing power of a single control agent."*
3. *"A decentralized approach is more appropriate in a network in homogeneous processors, each processor interacts with others as peers and the communication burden of resource allocation is equitably distributed among the processors."*
4. *"The information required at each step in the optimization process may itself be distributed throughout the system. Rather than transmitting this information to a central site at each iteration, the nodes may exchange this information among themselves and possibly reduce the communication requirements of the communication system or structure inherent in the problem itself."*

Next, Ygge [123] rephrased the above four criteria as (p. 39):

> Distributed computing is a delicate task and arguments that at a first glance seem reasonable often turn out to be poorly justified. One should not confuse the actual computation issues with the design issues, neither should the market communication between agents be confused with actual communication between hosts. That is, the fact that the involved agents might

> have been implemented and instantiated by difference companies at different places does not imply that they must remain at their hosts and that computation must be performed in a decentralized way (cf. TELESCRIPT, a language created by General Magic Inc.). Similarly, the fact that the market abstractions are used on design and implementation levels does not mean that the actual communication between hosts is based on corresponding message types.
>
> The above indeed gave a negative view of decentralized market computations. Are there any *good* arguments for decentralisation? We believe so. If the system grows extremely large, including many thousands, or even million agents, and there is plenty of computation capacity inherent in the system, it can pay off to distribute the computation. Furthermore, if global communication is expensive, but if there are local networks in which the communication is cheaper, it makes a lot of sense to try to aggregate the preferences of the agents of the different groups (i.e., belonging to the different local networks). [...]
>
> At the same time, one should carefully keep in mind that advantages of decentralized computing should not be credited only to market approaches. For example, decentralized computing with Lagrangian multipliers rather than prices (or marginal utilities) as the main abstractions is certainly conceivable [48].

4.5.2 MBC vs. CC

Following the comparison of DC and CC structures, we now tighten our review to consider MBC versus CC comparisons. Here, the thesis of Kroll [61] is very insightful. He explores the reasons for which market mechanisms are not a source of inspiration to design optimization algorithms as good as, for example, genetic mechanism and neural networks. Since his conclusions are not supported by a formal model or by (simulated or empirical) data, we may well argue with parts of his reasoning. For instance, Brewer [11] (p. 43) proposes to use auctions in order to *"create a decentralized computer that can solve any of the mathematical problems that a centralized computer can solve."* As we saw in Subsection 4.3, he achieves this in a specific domain by replacing the central computing aspect of the Binary Conflict Ascending Price (BICAP) auction by the Computation Procuring Clock Auction (CPCA).

Next, Kurose and Simha [65] have not only proposed the previous four arguments pro-DC, but they also claimed that such economic-based algorithms have *"several attractive features including their simplicity, distributed nature, provable (and rapid) convergence, and the computation of successively better resource allocations at each step"* (ibid., p. 705). Furthermore, Chevaleyre and colleagues [19] (p. 20), besides repeating the simplicity of the communication protocols in auctions, add the good performance of recent algorithms for combinatorial auctions. However, they also regret the difficulty to find an agent who can play the role of an auctioneer. Other sources support MBC, such as several of the articles in the book [21], in particular the preface of the book. Of course, it is also possible to find arguments in favor of CC, since you may have noticed that all those presented in this subsection are pro-MBC!

Finally, we would like to conclude this section about CS with King [60] who described a quarter of a century ago the debate over centralized or decentralized computing as a long-standing debate. His informal description of the advantages and drawbacks of both approaches concludes (ibid., p. 345) that *"changes in technology will not resolve the issue because the most important factors in the debate are grounded in constant reassessment of where control of organizational activities ought to reside."* As a consequence, installing a centralized or decentralized computer system may also be caused by human factors.

5 Evidence from Economics

Since Economics has an older literature than CS regarding the comparison of CC, MBC and DC, we now continue our review with this science. We do not attempt to translate these comparisons from Economics into CS, but review the raw evidence found by economists in order to gain insights into what might be expected in CS by adopting concepts from CC, MBC or DC. As with the CS literature, we first give an overview of the review findings, before presenting a more detailed review.

5.1 Overview of the findings in the economic literature

Firstly, we make the distinction between micro- and macroeconomics. Microeconomics *"portrays [...] estimates of economies of scales within a firm, demand and supply for a particular market, or the effect of a regulatory measure on a given industry"*, while, on the other side, macroeconomics *"forecasts key economic measures such as Gross Domestic Product (GDP), inflation, unemployment, interest rates, and international trade"* [105, p.197]. Notice that many of the results obtained in distributed CS are closely related to results in microeconomics; for example, some systems are simply implementations of results from microeconomics, such as the application of game theoretic concepts and results from Mechanism Design. On the other hand, there are relatively fewer macroeconomic comparisons in CS, even though some examples such the study of the cycles of centralization and decentralization of institutional information systems could be counted here.

Finally, comparisons of different organizational structures in both micro- and macroeconomics make use of all forms of evidence – informal claims, empirical data, simulation-based evidence and theoretical proofs – as shown in the summary of our review, presented in Table 6. The results presented in the second row of Table 6, concerning "coordination issues", were obtained using microeconomic theories and methods, while those in the third row, concerning "comparison capitalism vs. socialism", are macroeconomic in nature. In the remainder of this section we present the detail underlying this summary table, according to the nature of the evidence adduced for comparisons – deductive theoretical proof, empirical studies, and informal claims.

Topic and reference	Type of evidence	Result	Type of comparison
Coordination issues (Microeconomics):			
-Tragedy of the commons:			
. [46]	Informal	All worse off without coordination.	CC/DC
. [44]	Formal	All worse off without coordination.	CC/DC
- Prisoner's Dilemma (PD):			
. [72]	Formal	Both worse off without coordination.	CC/DC
- Iterated PD (IPD):			
. [7]	Simulation	Coordination emerges with repetition.	CC/DC
Comparison capitalism vs. socialism (Macroeconomics):			
- USA vs. USSR:			
. [62, 63, 64]	Empirical	USSR $>$ USA.	CC/MBC
- West vs. East Germany			
. [33, p. 304-6]	Empirical	1) West $>$ East Germany, and 2) Greater dispersion of West Germany efficiency.	CC/MBC
- North Korea vs. South Korea			
. [51]	Empirical	N. $>$ S. Korea in 50s and 60, and $<$ later on.	CC/MBC
- Many soc. vs. cap. economies:			
. [42, 32]	Empirical	1) Diversity of efficiency of capitalist economies $>$ socialist eco. 2) Variations among a system $>$ variations between systems.	CC/MBC
. [14]	Empirical	Capitalism $\approx$ socialism w.r.t efficiency.	CC/MBC
. [66]	Empirical	Capitalism $>$ socialism w.r.t efficiency.	CC/MBC
. [98] & [87]	Empirical	Capitalism $<$ socialism w.r.t life indicators.	CC/MBC
Attitude towards decentralization:			
- [30]	Empirical	Model in Figure 11.	CC/DC

Figure 6: Comparisons in Economics.

5.2 Theoretical proofs in Economics

During the twentieth-century, mainstream economic theory increasingly used sophisticated mathematical models, and this trend continues to drive the discipline [120]. The issue we are considering in this paper has been studied by mathematical economics working in Game Theory, the study of multi-party economic interactions, and Mechanism Design, the design of economic marketplaces.

5.2.1 Game Theory

Game Theory is that part of mainstream Economic Theory which models economic interactions between rational entities, called agents. Being rational (in some sense), such agents consider the likely decisions of each other before making their own decisions. This theory was first developed formally by von Neumann and Morgenstern [118] in order to represent and study strategic behavior in multi-party interactions. More precisely, *"a game is a formal representation of a situation in which a number of individuals interact in a setting of strategic interdependence. By that, we mean that each individual's welfare depends not only on her own actions but also on the actions of the other individuals"* [76, p. 219].

Game theorists have been concerned with the strategies which rational entities would adopt in such interactions, a notion called a *solution concept*. The most common solution concept used in Game Theory, the Nash equilibrium [86], formally expresses that *"each player's strategy choice is a best response to the strategies actually played by his rivals"* [76, p. 246]. The Nash equilibrium, as well as many of its refinements, has been used to study coordination problems, that is, why are agents not able to make decisions that are at the same time the best for themselves and for other agents? Game Theory has had the following offspring:

- *Empirical Game Theory* is the use of simulations of games to analyze situations or domains where analytical game-theoretic models are mathematically intractable, for example where there are many players or many possible strategies [34]. We previously mentioned this approach in Subsection 5.3 regarding its application to the Trading Agent Competition - Supply Chain Management (TAC-SCM). We know of no use of Empirical Game Theory to compare CC vs. MBC/DC organizations.

- *Iterated Game Theory* studies situations where a game among a collection of players is played repeatedly, possible infinitely often. One special branch of Iterated Game Theory, called *Evolutionary Game Theory*, considers repeated games where participants may change their strategies at any one round on the basis of their past experience in previous rounds; in other words, participants may learn, or the population of strategies may evolve. We shall discuss an important iterated game, the Iterated Prisoner's Dilemma (IPD), below.

5.2.2 Mechanism Design

Mechanism Design is the study of market mechanisms and economic systems, and their design and creation. In an early review of Mechanism Design, Hurwicz [50, p.

1] introduced this topic as *"finding a system that would be, in a sense to be specified, superior to the existing one."* He next recognized that this *"idea of searching for a better system is a least as ancient as Plato's* Republic*"*. This is the same goal as that of the designers of socialism (cf. the comparison of socialism with capitalism in Subsection 5.4), in other words, the development a new and better economic system. Hurwicz [50] also reviewed the procedures (i.e., algorithms) and mathematical tools available to allocate resources either in a centralized way (e.g., simplex method, Lagrange multipliers, etc.) or in a decentralized way (e.g., Dantzig-Wolfe decomposition, etc.), which were discussed under the hearing of Operations Research in Subsection 4.2.

Why is Mechanism Design theory relevant to this survey? The key result of Mechanism Design is the Revelation Principle which, under suitable assumptions, *"establishes that central control cannot be dominated by any delegation arrangement. Specifically, it demonstrates that the outcome of any decentralized organization can be mimicked by a centralized organization in which the responsibility of each agent is merely to communicate their information to a central authority and await instructions on what to do."* [81, p. 369][14]

5.2.3 The General Equilibrium

Both Game Theory and Mechanism Design deal with decision making in general, i.e., not particularly with marketplaces.[15] We now outline the theory of the General Equilibrium, which deals with markets.

General Equilibrium theory is *"a theory of the determination of equilibrium prices and quantities in a system of perfectly competitive markets."* For that purpose, this theory *"views the economy as a closed and interrelated system in which we must simultaneously determine the equilibrium values of all variables of interest"* [76, p. 511]. Let us illustrate what is addressed by this theory. Assume that the price of some product A rises. As a consequence, some buyers of A may react, some by buying more of the product and some by buying less; those who buy more of A may do so in in anticipation of future price rises from which they can profit by holding stock of the product. Other buyers of product A, however, may react to a price rise for A by buying more or less of some other product, B. If A and B are complementary goods (i.e., each is needed to gain full utility of the other), then a rise in the price of A may lead to a fall in demand for B. If A and B are substitute goods (i.e., each can provide much the same utility as the other), then a rise in the price of A may lead to a rise in demand for B. These reactions in turn alter demand levels for B and hence its price. The change in price of B may then, in turn again, lead to changes in the price of A, again leading to changes in its demand, and so on. In such a context, what is called the general equilibrium is a stable vector of prices, one price per product, so that no further changes occur to this price vector.

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[14] Recently, economists and computer scientists have collaborated to develop a new field, Algorithmic Mechanism Design, that tries to design algorithms not able to be manipulated by the agents interacting under an economic mechanism. Specifically, some agents may find it preferable not to follow a given algorithm, and the goal of Algorithmic Mechanism Design is to build algorithms so that this does not happen [90].

[15] We have already introduced TAC-SCM, but the Trading Agent Competition (TAC) also has a track called TAC Market Design – see `www.sics.se/tac`.

Bryant [13] reviews the literature in mathematical economics on the existence of such a general equilibrium, and the conditions necessary for its achievement. If there exist price-quantity states of an economic system from which such equilibria are unattainable, then the concept of equilibrium becomes problematic (ibid., p. 3). Bryant concludes that nobody has yet proposed a universal, globally stable and realistic tâtonnement process to find a general equilibrium. Specifically, some proposed processes fail to converge while others require implausibly large amounts of information (ibid., p. 26); typically, each agent needs to know the second partial derivatives of its own demand functions for all products with respect to changes in price – in other words, the second partial derivative of a consumer's demand for gasoline when there is a change in the price of butter, and so on for all products.

Computing the general equilibrium of a capitalist economy is very difficult, and is similar to the economic calculation addressed by the Central Board Planner in a socialist state. We have not found any formal literature about the latter problem, while the former has been much investigated – see textbooks as [54, chap. 5]. In fact, concerning its socialist counterpart, we have only found some informal claims, such as Von Mises [117] who thought the economic calculation intractable for a socialist economy, conversely to Oskar Lange who proposed to solve it with the same simple method of trial and error used in capitalist economy, also known as Walras's *tâtonnement* process [68, p. 63]. Similarly, Land and his colleagues see capitalism as a decentralization by the dissemination of price, while socialism is another form of centralization in which purchase quantities are enforced by central decree (we have already spoken about price- and quantity directed approaches in Subsection 4.2). It is interesting to note that they see capitalism and socialism as two ways to solve problems looking *"astonishingly alike"* [67, p. 140]. From a political point of view, Ellman [33] (p. 315) also claims these two economic systems are similar because they both use democracy, where he defines democracy as a system in which *"social choices [are] determined by all the members of society."* However, the type of democracy in these two systems is different (ibid., p. 315):

- The democracy in *capitalism* is *liberal*, which means that *"individual choices are [assumed to be] both unconcerned with, and independent of, the choices of other individuals."*

- The democracy in *socialism* is *totalitarian* in the sense that *"the decision making process [is assumed to] normally correspond to the Prisoner's Dilemma (PD) situation."*

We discuss the Prisoner's Dilemma (PD) below.

5.2.4 Coordination issues

General Equilibrium theory assumes economic agents each have preferences over the products they may purchase, and that these preferences are independent of one another, they are stable, and that each agents knows its own preferences before any economic interactions commence. For many economic interactions, however, the preferences of rational agents may depend on each other. The utility of a fax machine to any one consumer, for example, depends on whether other consumers also have fax machines; in such a situation, a rational agent would only decide what purchase decision to make after learning about the purchase decisions (or at least the preferences) of other agents. This situation where the outcome of a decision to one agent depends upon the decisions taken by other agents is common in economic domains, and leads naturally to a study of co-ordination of decision-making.

Within economics, co-ordination has typically been studied within a context of repeated interactions, for example in Iterated Game Theory. Let us first note how computer scientists often see coordination. Malone and Crowston [74] defined it as *"the management of interdependencies among activities."* We believe that this definition can be translated into the language of economists by replacing *"interdependencies among activities"* by *"externalities"*, where an externality is a side-effect, as reflected, for example, by this definition: *"an externality is an action taken by either a producer or a consumer which* affects other *producers or consumers but is* not accounted for *by the market price"* [100, p. 294]. As a consequence, coordination models consider the difficulty of individuals to take fully into account interdependencies among their activities/externalities when making decisions in interactive situations; the result of a failure to take these factors into account are overall decision-outcomes which are less efficient than they would be otherwise. This would imply that Decentralized Control (DC) may not achieve optimal outcomes. One solution to such difficulties can be the centralization of decision making. Another solution is to allow distributed decision-makers to exploit past experience in repeated interactions, as we shall see with Iterated Game Theory in Subsection 5.3.1.

Let us now turn our attention to the Tragedy of the Commons, proposed by Hardin [46] to describe situations where common resources may be overconsumed. Gravelle and Rees [44] define such commons as *"assets whose services are used in production or consumption and which are not owned by any one individual, [. . . e.g.] ocean fisheries (anyone may fish outside territorial waters), common gazing land (anyone satisfying certain requirements, such as residence in a particular area, may graze as many cattle as they wish on the land) and public roads (any motorist with a valid driving license may drive a roadworthy insured vehicle on public roads)"* (ibid., p. 522-525). [44] gives a formal representation of the Tragedy of the Commons (p. 522-525).

The Tragedy of the Commons can be seen as a multi-player generalization of the Prisoner's Dilemma (PD), since this latter model has only two players. PD is probably the most famous non-zero-sum game in Game Theory. Luce and Raiffa [72] (p. 94-5) present this game as the two matrices in Figure 7. As with any game in the normal form, Figure 7(a) should be read as follows: when Prisoner 1 chooses Strategy α_1 while Prisoner 2 uses Strategy β_2, then Prisoner 1 has payoff 0 while Prisoner 2 has 1. Figure 7(b) gives a more concrete interpretation of Figure 7(a) with the time spent in jail against one's and other player's strategy. As can be seen, this is a problem of coordination between the two prisoners, because both are better off when they coordinate with each other, thus, play (α_1, α_2), but this outcome does not occur when prisoners act independently. In fact, both have incentives to confess:

- If Prisoner x ($x \in \{1, 2\}$) chooses Strategy 1 (α_1 or β_1), then the other Prisoner $\bar{x}$ is better off if he betrays x by playing Strategy 2 (α_2 or β_2);

		Prisoner 2:	
		β_1	β_2
Prisoner 1:	α_1	0.9, 0.9	0,1
	α_2	1,0	0.1,0.1

(a) Matrix of payoffs to maximize

		Prisoner 2:	
		β_1	β_2
Prisoner 1:	α_1	1 year each	10 years for 1 & 3 months for 2
	α_2	3 months for 1 & 10 years for 2	8 years each

(b) Interpretation in terms of years in a penitentiary to minimize

Figure 7: The Prisoner's Dilemma [Luce and Raiffa 1958, p. 95].

- If Prisoner x ($x \in \{1, 2\}$) chooses Strategy 2 (α_2 or β_2), then the other Prisoner $\bar{x}$ is better off if he also betrays x by playing Strategy 2 (α_2 or β_2).

In summary, whatever Prisoner x chooses (Strategy1 or Strategy2), the other Prisoner $\bar{x}$ will betray (always Strategy2, i.e., α_2 or β_2). As a consequence, both prisoners will betray each other by playing their Strategy2, and the worse outcome for both Prisoners will occur. Technically, we say that (α_1, β_1) is the only dominant strategy equilibrium. We may also check that (α_1, β_1) is the only Nash equilibrium of the game.

We now review the evidence based on simulation by continuing this presentation of the PD when this game is iterated.

5.3 Simulation-based evidence in Economics

Apart from simulation studies of the Iterated Prisoner's Dilemma game, which we review immediately below, we have found no other economic simulation studies relevant to the questions of this review. In large part, this absence may be due to a systemic bias in the Economics discipline against undertaking and/or publishing simulation studies, as we noted above.

5.3.1 Iterated Prisoner's Dilemma

The Iterated Prisoner's Dilemma (IPD), also known as PD supergame, assumes the same players play several PD games in sequence. Every player earns the total of these repeated games, or rounds. Axelrod used computers in order to show that players had long-term incentives to cooperate in order to obtain the payoffs associated with (α_2, β_2), instead of getting stuck on the lower payoffs given by (α_1, β_1) [7, 5]. It was also found that the tit-for-tat methods of selecting a strategy in every round won the tournament ran against other methods.

In addition to lack of coordination among prisoners, the (normal or iterated) PD has also been interpreted in other ways in order to study lack of coordination in other domains, such as [114, Sect. 3]: everyday life (e.g., keep a forest tidy [97], disputes between neighbors. love, etc); economics (e.g., the study of oligopolies, border barriers, labor contract, free rider problem, etc); biology and evolution (development of bacteria, and territory defense by birds follow tit for tat, etc); morality, politics and philosophy (American senators play tit for tat against other senators when attracting votes, competition between states, etc); wars, etc.

5.4 Empirical data in Economics

All the published studies found within Economic which use empirical data to compare CC vs. MBC/DC compare socialism with capitalism. The material below was mostly reviewed by Ellman [33], but we have also included more recent material, e.g., [51] and [66]. As will be seen, most of this literature compares the productivity indices of instances of capitalist and socialist economies in order to assess the respective efficiency of these two systems.

We begin this subsection with some methodological comments, before presenting comparisons of pairs of countries, e.g., USA vs. USSR, then comparisons of groups of countries.

5.4.1 Methodological issues in comparisons of national economies

Many biases may occur when attempting to compare economic systems by comparing their instantiation in different countries:

- *Delays may make comparisons more difficult* as illustrated by Kudrov [64] who noticed that the transition of Russia from communism to capitalism has not made its economy grow straight away, but several years later.

- *Statistical data are subject to different definitions* in different countries or at different times. It may also be that some concepts are not well-defined under some economic systems. For example, [33] (p. 302) criticizes [62] about the fact that *"the statistics for the European Economic Community (EEC) and the Council for Mutual Economic Assistance (CMEA) are non-comparable. The EEC statistics use the SNA method and the CMEA statistics the MPS method."* Similarly, Gross Material Product (GNP) measures the income received by the residents of a capitalist country, which differs from the Gross Social Product (GSP) used to assess the productive activity carried out by a socialist economy [51, p. 93-4]. Hwang illustrates this with the following example (ibid, p. 102):

  > Suppose that a particular farm co-operative produces 10 units of wheat, of which 2 units are consumed by the co-operative itself. A wheat mill uses 8 units of wheat to produce 20 units of wheat flour, of which 5 units are consumed within the mill. Next, a bakery purchases 15 units

of wheat flour to make 30 units of bread and it consumes 10 units of bread out of this 30 units. Then the GSP earned in these productive processes is 43 units: (10-2)+(20-5)+(30-10)=43. But in terms of the GNP concepts used in market-type economies, this would come to 37 units: 10+(20-8)+(30-15)=37.

- *Statistical data may be subject to manipulation* in favor of particular ideologies because they are usually collected by Governments. Regarding this, Ellman [33] (p. 302-3) amplifies the critique of Kudrov [62] mentioned in the previous bullet by claiming that *"CMEA statistics are coloured by 'the propaganda of success,' [that] is a Polish phrase of the 1970s. It refers to the then official Polish practice of extravagant praise of achievements and projecting temporary successes into the future; combined with the maintenance of silence or the dissemination of falsehoods, about current problems and difficulties and possible future problems."* In addition, it is interesting to see that the conclusions by [63] regarding the comparison of the USA and USSR economies seem[16] to be the opposite to those by Kudrov [62] 20 years earlier.

- *We may not be comparing like-with-like* because different countries are at different stages of economic development [14, p. 1115-6] or because they have different industry structures. According to a review by Hwang [51], North and South Korea seem to be the best pair of countries to compare, since they were *"remarkably equal at partition"* [20, p. 1389]. However, the two Korea were not exactly equal, e.g., at the time of partition, some 75% of the heavy industry was north of 38th Parallel and 75% of the light industry south [51, p. 22].

- *We cannot easily control for non-economic factors*, such as culture, religion or history [33, p. 299]. For example, West and East Germany are quite similar but *"differ in scale, relationship to superpowers and opportunities for trade"* [14, p. 1116].

As a consequence, comparing capitalism and socialism through examples is a very problematic exercise. Despite this, economists have tried to overcome these many problems in order to compare the USA and the USSR, as now presented.

5.4.2 USA vs. USSR

Among the empirical comparisons of capitalism and socialism, most studies concern the comparison of the USA and USSR. The most interesting are [33, Chap. 10], [63], [14], and the publications of the Central Intelligence Agency (CIA) of the USA. Again, we focus here on empirical data.

We focus our attention on the work of Valentin Kudrov [62, 63, 64], as presented in [33, p. 301], who was the leading Soviet specialist on the comparison of the USA and the USSR. His 1997 paper presents data from an unpublished 1975 manuscript, and was only made available publicly recently. As indicated by its name, this paper was

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[16] We write "seem" rather than "is" because we cannot read Kudrov's original paper [62] written in Russian, and can thus only rely on [33, p. 302].

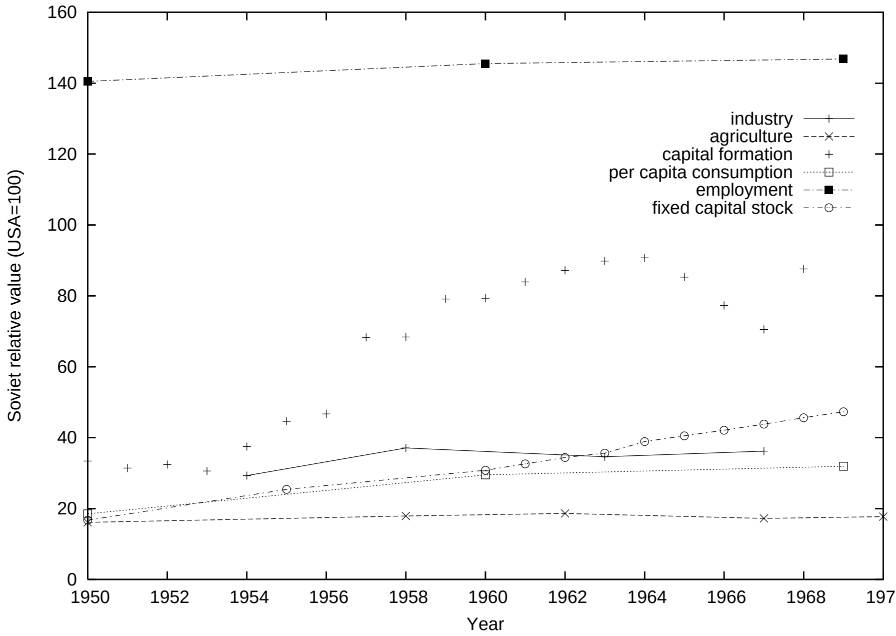

Figure 8: Macroeconomic indices of the USSR relatively to the USA [Kudrov 1997].

produced by the Institute for the World Economy and International Relations (IMEMO) of the USSR Academy of Sciences. This manuscript was kept secret because it did not support the official Soviet comparisons of the USA and the USSR, but supported, rather, the conclusions reached by the CIA comparisons. As with all work comparing different economies, the paper extensively explains how the data were collected, and homogenized in order to take account of the different statistical techniques used to aggregate raw data in the two countries. Figure 8 summarizes six macroeconomic indices in the USSR with regard to their level in the USA (base 100 for the USA) drawn from [63].

The first comment to make regarding Figure 8 is that the Soviet economy slowly catches up to US levels in 1950–1970. Unfortunately, according to Ellman (who cites two official sources, namely the official Soviet handbooks and the director of the USSR Gosplan's economic research institute), this situation changes in 1976–1985 because the Soviet national income per capita slightly fell and labor productivity in agriculture fell in this period, which suggests that *socialist economies may incur crises*, as capitalist ones do (ibid., p. 303). As a result, Bergson concluded that [9, p. 111]:

> In sum, to come to the question of ultimate concern, there is further evidence of how far socialism is economically from the chaotic system critics once held it would be and from the potent mechanism that proponents have often envisaged. At least, the Soviet variant of socialism seems nei-

Country	Capital stock per worker with labor		Factor productivity with labor	
	Unadjusted for quality	Adjusted for quality	Unadjusted for quality	Adjusted for quality
United States	100	100	100	100
France	49	55	71	78
West Germany	37	45	69	79
United Kingdom	33	37	61	66
Italy	32	39	60	70
USSR	50	63	58	68

Table 9: Capital stock per worker and factor productivity in industry in 1960 [Bergson 1978, Table 7.7].

> ther colossally wasteful nor extraordinarily efficient but well within the extremes that are so familiar in polemics on socialist economics. The Soviet system, however, appears to be undistinguished by Western standards.

This insight seems to be confirmed by Figure 10 in which we will see that the variance of performances of socialist economies seems to be smaller than that for capitalist economies.

The second comment to note on Figure 8 is that all indices are lower in the USSR than in the USA (i.e., below 100), with the exception of the proportion of the population employed; in the USSR, this 1.5 times greater than in the USA. This difference could be due to historical reasons, such as the destruction of the USSR's capital infrastructure during the second World War, and hence a greater reliance on labor inputs. Another explanation may be the fact that the USSR employed more people than was typical for its stage of development, but rather that the USA employed fewer than were typical. Bergson [9] supports this explanation in his Tables 7.5 to 7.7 (his Table 7.7 is reproduced in our Table 9), which shows that the USA in 1960 was untypical of other capitalist countries in its use of labor.

This empirical data would support the conclusion that the economic efficiency of the USA was greater than that of the USSR. We now consider other comparisons of socialist and capitalist countries.

5.4.3 The two Germany and the two Korea

The comparisons of the two Germany and the two Korea are much more insightful than the comparison of the USSR with the USA, because in both cases, these pairs of countries are quite similar with regard to their culture, history, land, industry, etc, although in neither case are the pairs identical. Our main findings regarding these two countries from this survey are:

- *West and East Germanys*: Ellman [33] summarizes several earlier studies about the two Germanys by stating that *"in the post-war period the level of productivity in [West Germany] has consistently been above that in the [East Germany], but* *the growth of this productivity depends on "the period considered, the treatment of unemployment and female non-employment, and the data used."* He finally points to the fact that the *"biggest difference between the data for the two countries for this period is the greater dispersion of the series for the [West Germany] resulting from the greater instability of a capitalist economy"* (ibid., p. 304-5), as will be confirmed by Figure 10.

- *North and South Korea*: Ellman considers that studies comparing two Koreas available in 1989 are not very accurate (ibid., p. 304). Later on, the book by Hwang [51], a South Korean, was welcomed by [20] and [91], even if they do not agree with its content entirely. However, several sources seem to agree that the North Korean economy grew faster than that of South Korea from the end of the Korean War to 1969 (according to the South Korean government) or to 1976 (according the the CIA) [51, p. 119]. This corroborates the estimation of North and South Korean GNP calculated by Hwang and displayed in Figure 9.

Finally, China is a third example of country split between socialism (People's Republic of China) and capitalism (Republic of China – Taiwan). However, these two nations are much more dissimilar than in the case of the two Germanys and the two Koreas, in terms of size, natural resources, history and culture.

5.4.4 Many socialist economies vs. many capitalist economies

Another interesting way to compare capitalism and socialism is to consider several economies from each system. Gomulka [42] compared the static and dynamic efficiencies of several socialist and capitalist countries. The result of his work is contained in Figure 10, which figure is that of published by Dirksen [32] after the latter added China to the analysis. In this figure, the upper dotted line shows the countries which are empirically believed to perform best, while the lower dotted line the countries which perform less well, according to different levels and growth of labor productivity. The main two conclusions drawn from this figure are [33, p. 306-7]:

- *The diversity of dynamic efficiency is greater with capitalist countries than with socialist economies*, i.e some capitalist countries perform very well and some other very badly while all socialist countries are between these two extrema. In other words, *"capitalism appears as the more unstable system"* [33, p. 306]. [62] (p. 17, cited in [33, p. 305-6]) also presents the greater stability of socialism as an advantage over capitalism.

- *We find more variation among countries with the same system than variations between the systems themselves.*

This lesser variance of performance of socialism, previously encountered in the studies of the two Germany, seems to be an important feature of this system.

Next, Burkett and Skegro [14] compared the economic growth that socialism and capitalism achieve under different level of development, in the same way as we saw in Figure 9 that the North Korean economy grew faster than the South Korean one from the end of the Korean War to the late 1970, then the situation was the other way around [51, p. 87]. To undertake this analysis, Burkett and Skegro used a method proposed by Leamer [69] to study the 1975 data on 65 countries regarding 11 resources, viz. capital, three grades of labor, four kinds of land, minerals, coal, and oil and gas. They investigated the following two contradicting claims: proponents of socialism claim that capitalism becomes less efficient with development because of *"rising unemployment, worsening monopolistic distortions, and declining capacity utilization,"* while opponents of socialism respond that socialism also becomes less efficient with development because *"socialist institutions are better adapted to mobilizing resources for industrialization than to providing the incentives and information appropriate to a developed economy"* [14, p. 1115]. These authors conclude that neither of these two points of view is better, since *"while the relative productivity of socialist economies may decline as capital-labor ratios rise, the net effect of socialism on productivity is insignificantly different from zero at all observed levels of the capital-labor ratio. These results are robust to adjustments for heteroskedasticity, deletion of any one country from the sample, and introduction of prior information on marginal products"* (ibid., p. 1130). As a result, these results indicate that the assessment of the two Koreas by Hwang [51] presented in Figure 9 is a particular case not representative of what may be observed in general.

In the same way, Land and his colleagues believe that one of the main differences between capitalism and socialism deals with their management of the uncertainties created by change. Indeed, while capitalism faces market uncertainty, socialism faces bureaucratic uncertainty [66, p. 110-1]. Then, they use mathematical programming to model both systems, and compare their efficiency by setting the stochastic properties to represent either system. Despite the fact this work is theoretical, we preferred not to report it in Subsection 5.2 but here in order to introduce its application to empirical data. The model was applied to 17 West European and 7 East European economies and found that, *"the capitalist economies have allocated resources much more efficiently than the state socialist economies have."*[67, p. 141]

Other studies of economic factors as productivity levels and growth also exist, such as [52], who compared south-western and south-eastern European countries, but we now turn our attention to non-economic metrics such as life indicators. First, Petras [98] gathers data on former socialist countries to compare the 15-year period of transition to capitalism with the previous 15 years of socialism: he finds the socialist period is superior to the capitalist-transition period on almost all quality of life indicators. Examples of such indicators include levels of HIV/AIDS (which have risen in Eastern Europe and Central Asia from fewer than 10,000 people in total, to 30,000 in 1995, and to more than 1.5 million in 2004). Similarly, Navarro [87] compares health indicators such as life expectancy at birth, infant mortality, or the rate of illiteracy. These studies seem to show greater quality of life under socialism than under capitalism, at least for the period of transition to capitalism. Such differences may, of course, be artifacts of the transition rather than true indicators of underlying differences between the two systems.

5.5 Informal claims in Economics

We conclude this section on the economics literature with an overview of informal claims in Economics. In the first half of the 20th century, there was an intense debate between economists arguing for or against either capitalism or socialism. On the socialist side were authors such as Barone [8], and Lange [68], while they were opposed from the capitalist side by authors such as Hayek [116] and Von Mises [117]. Besides these ideological disputes, Pigou [99] informally compared socialism and capitalism taking England and Russia as examples of his demonstrations, and Noyes [93] edited a book in which several authors informally compared different economic and social systems around the world. In all this work, claims are supported by informal arguments; in other words, authors use neither deductive theoretical proofs, nor simulation, nor empirical data to support their case.

The arguments presented by debate between proponents of capitalism and proponents of socialism is used by Devries [30] to review the arguments for and against CC and DC in public policy making; he concludes, *"that the same arguments are sometimes used to advance either claim and that in different countries opposite arguments are used to support the same claim."* He illustrates this with what he calls the *"fantasy of the optimal scale"* by comparing a nation-state like the Netherlands (16m inhabitants) with cities like New York (19m inhabitants); decentralizing responsibilities to such a large city would be called centralization in the Netherlands! This makes *"the inherent features of centralization and decentralization far from obvious,"* and may explain why *"centralization, decentralization and recentralization [. . .] seem to be ongoing cycles in which trends and taking side in the discussion succeed one another continuously."* This very interesting paper presents informal claims about the respective efficiency of centralization and decentralization before exploring the empirical data influencing public opinion toward decentralized responsibilities in some Western European countries. The goal of Devries [30] is not to determine whether CC or DC is the best approach in some sense, but to understand what is perceived by local elites to be the best depending on the issue under consideration. This data is next used to propose a model linking some factors to the probability that local elites will be *"in favor of local co-responsibility on separate issues."* As can be seen in Figure 11, this probability is negative when the concerned issues are the "unemployment" (-0.15), "health-care" (-0.12) and "quality of education" (-0.08), which indicates that these local elites think they should not manage these questions, conversely to policies on "public improvements" (+0.16), "housing" (+0.12) and "culture and recreation" (+0.10). This figures also indicates that the "size of the country," the "openness" (e.g., width of local contacts) and the "public participation" are associated with the "general opinion on decentralization", which has itself a great impact on the probability to be "in favour of local co-responsibility on separate issues." Finally, "personal influence" on an issue area and the "autonomy at the local level" indicate the power of local elites on the considered issue area. This study recalls the statement of Janssen that a decision to centralize depends not only on the available technology, but also on stakeholders' motives, goals and roles [53].

Similarly to Devries [30], Cummings [26] investigated the cycles of centralization and decentralization by addressing the question of the existence of an equilibrium around which these cycles revolve. He concludes that *"the dynamic between the two forces is based upon continual flux and movement, no balance will ever be reached, and any notion of a linear direction [e.g. only decentralization] is only true if not viewed within a broad historical context"* (ibid., p. 115). Specifically, the pendulous movement between the two forces is more driven by its internal dynamic than by the external environment (e.g., managerial styles and technological developments). This latter conclusion contradicts what we saw in CS [96], as well as Hurwicz [50] (p. 5) who explained that the availability of the simplex method favored centralization, thus socialism:

> But around 1950, linear models were in fashion. Furthermore, the simplex method was available and proved to be convergent. Since the simplex method, applied to the economy as a whole, lacked informational decentralization, a search for an alternative was bound to occur. For the economist, an obvious candidate was a simulated (perfectly competitive) market à la Lange, Lerner, and (specifically in the context of a linear economy) the Koopmans model.

In fact, *"Oskar Lange and Abba Lerner [claimed] in the 1930s socialism debate that incentive properties of the decentralized mechanism can be replicated by a suitably designed centralized mechanism"* [81]. However, these conclusions based upon informal arguments may turn out to be false when the specific constraints of the real world are taken into account. In this regard, Mookherjee [81] also presents *"Hayek's counterarguments in the socialism debate, that excluding considerations of communication cost or limited information processing capacity of the central planner is like throwing out the baby with the bathwater."* In particular, we saw in Subsection 4.5 regarding Computer Science that centrally simulating a decentralized algorithm may not be feasible in practice for different reasons (information confidentiality and bulk, tractability issues, etc.).

6 Conclusion

This paper has reviewed the literatures on comparisons of Centralized Control (CC), and Market-Based Control (MBC) and Decentralized Control (DC) approaches in Computer Science (CS) and in Economics. While comparisons based on deductive theoretical analysis of formal mathematical models have played a large part in supporting claims regarding the superiority of one structure over another within economics, comparative claims have also been supported by simulation studies, by the analysis of empirical real-world data on economic performance, and by informal arguments. We have reviewed the literature in both economics and computer science which uses these different types of argument, while focusing most of our attention on studies involving simulation or which use empirical data. We have paid less attention either to deductive theoretical arguments because these can be readily consulted in the mathematical economics literature, or to claims supported only by informal evidence, since these are difficult to compare and evaluate.

The main insights gained from Economics seem to indicate, firstly, that the performance efficiency of CC has a lower variance than MBC, even if, secondly, that neither CC nor MBC has a better efficiency on average. These two insights may explain why evidence from CS seems to support the fact, thirdly, that corporate computer systems typically cycle between centralized and decentralized organizational structures [96, 107]. A fourth insight is that there are relatively-fewer published studies based on simulations than are ones using empirical data. We would expect simulations to be cheaper to undertake than empirical studies, but this observation is probably due to the fact that inexpensive computational resources only became widespread recently; this finding may also be the outcome of some hostility to simulation studies within economics [75]. We also found very little evidence for claims of the type, *"under conditions X, Y or Z, centralized (or decentralized) control of system A is better than other forms of control when assessed against the specific metric M."* The only examples of such supported claims found were the works of Davidsson and colleagues [29], Schuff and Saint Louis [107] and Tan and Harker [110]. Finally, we have found no reports of failures with any of the three forms of organization.

A key conclusion from this survey is that further comparisons of simulated CCs with simulated MBCs should be undertaken in order to understand the circumstances under which one approach is better than another, against particular metrics of assessment. Such circumstances may involve issues such as: computational processing availability; information availability and dissemination; extent of environmental turbulence; etc. These comparisons could be undertaken via simulation, after some effort to better formalize the many informal claims; or they could be undertaken by means of deductive proof on mathematical models which better approximate real-world systems. In future work, we intend to implement simulation studies in this direction, continuing our prior work in models of supply chain networks.

Acknowledgments

We are grateful for financial support from the UK EPSRC, through project *Market-Based Control of Complex Computational Systems* (GR/T10657/01). We also thank Andrew Byde, Archie Chapman, Enrico Gerding, and Nicholas Jennings for their comments and suggestions.

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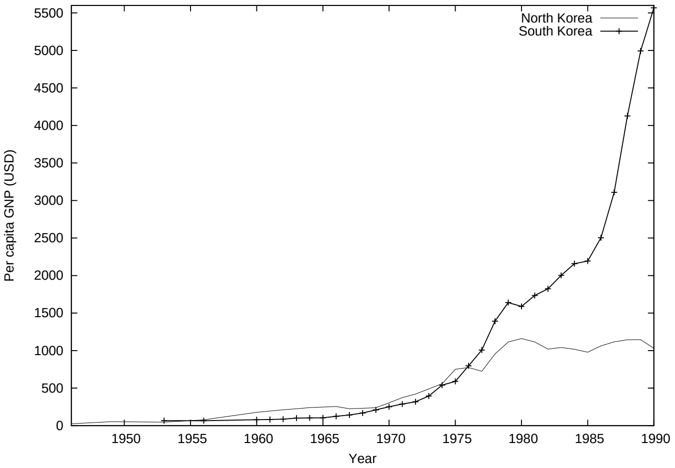

Figure 9: Estimation of per capita GNP for North and South Korean [Hwang 1993, Tables 3.11(a–b)].

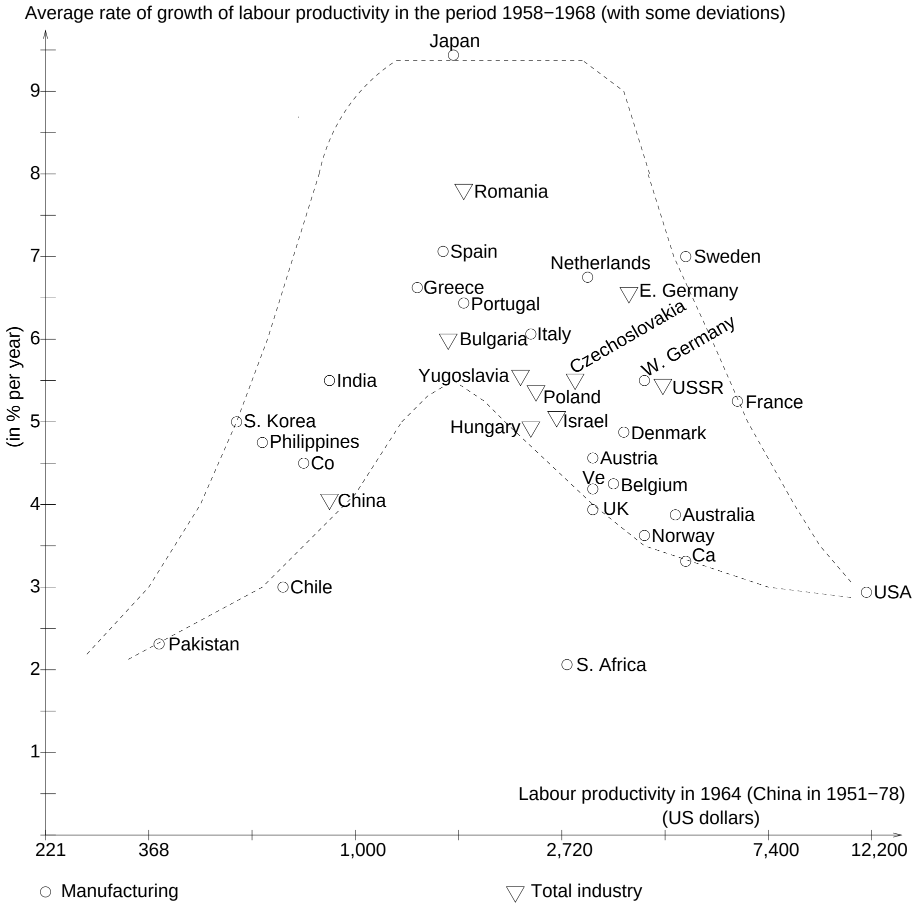

Figure 10: International dynamic efficiency (data for China in 1952-78 added by Dirksen [1983] over the data previously provided by Gomulka [1971] for the rest of the world in 1958-68).

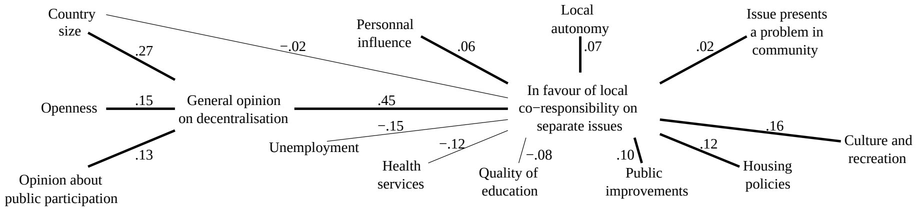

Figure 11: An explanatory model on opinions toward decentralized responsibilities [de Vries 2000].