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Collaborative Control Theory and Decision Support Systems

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Abstract

Collaborative Decision Support Systems, CDSS, depend on cost-effective collaboration among the decision participants. Those may include, in addition to human decision makers, non-human entities such as robots, software and hardware agents, sensors, and autonomous instruments. The purpose of this article is to explore the impact that CCT, the Collaborative Control Theory, has on cyber supported augmentation of collaboration in general, and its proven and potential impacts on CDSS in particular. Three recent case studies are discussed. The correlation between CDSS decision process and quality; and the level of CCT-based collaboration augmentation and the resulting level of Collaborative Intelligence, CI, is presented. It is concluded that while there are clear positive impacts of CCT based augmentation and level of CI, they need to be measured and optimized, not maximized. Further research in this area is also described.

Key Words: CCT-based Collaboration Protocols; Co-Insight; Collaboration Augmentation; Collaborative Intelligence; Collaboration Requirements Planning; Error and Conflict Prevention

1 Introduction

The significant research on decision making and taking by Academician Florin G. Filip,e.g., [17,18], and the recent publication of Filip et al. book on CDSS [19], *collaborative decision support systems*, offer an opportunity to analyze the mutual relations between CDSS and

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CCT, the *Collaborative Control Theory*. The book discusses in detail the role of collaboration in DSS, *Decision Support Systems*, the various processes and protocols of collaboration among the human decision makers, and the enabling computer, communication, information and cyber technologies that make CDSS increasingly more feasible, and sometimes more effective (e.g., [4], [5], [6], [54], [33], [35], [39], [42], [49], [50], [56]). It also discusses the fact that while the common team of decision makers are human, increasingly the participants are distributed, decentralized, and include software and hardware agents, robots, and machines. In particular, in real-time decision making and control, the heart and brain of smart and autonomous automation, the role of the automated, often autonomous non-human participants carries a larger responsibility.

Several questions arise in this context for control and automation engineers and scientists, and these questions can be presented by two key problems:

- What are the risks and what is the balance of these risks compared with the advantages of CDSS?
- How can such CDSS be designed, operated and maintained to minimize those risks while maximizing the benefits?

These problems are not new, as they have been asked and addressed by researchers and practitioners since computerized DSS first appeared. When additional computational resources at higher levels of cyber sophistication and power are added, these problems become even more acute. With greater advantages in supporting decision processes, come greater risks.

The purpose of this article is to address these problems from the perspective of CCT. The Collaborative Control Theory emerged when it was realized that internetworked, interconnected automation systems become so complex and interdependent that they will collapse unless designed and even optimized for effective and cyber-supported collaboration.

The article includes four sections following this introduction: Risks and advantages of collaboration in CDSS; CCT augmentation to overcome collaboration limits and risks; Collaborative Intelligence (CI) by CCT augmentation of CDSS; conclusions and further research.

2 Risks and Advantages of Collaboration in CDSS

Who collaborates on decision making and decision taking? Why do they need and why would they want to collaborate? Let us consider the functions of collaboration shown in Table 1, and the examples shown in Table 2. They illustrate who collaborates, the purpose of their collaboration, the motivation to reach and implement decisions, and some of the risks involved.

Revolutionizing collaboration by cyber support, including the case of CDSS, carries a large number of advantages (Figure 1). Some of them can be considered *mandatory collaboration requirements*, meaning that without them no good decisions can be analyzed and made. For instance, in a design case, without timely data from customers about the details of their demand, and from suppliers about their capacity availability to deliver, no correct decision can be expected. Errors and conflicts can be expected. Over large supply networks, and with inevitable changes and modification in supplies and demands, these mandatory collaboration requirements scale up and escalate.

Optional collaboration requirements are those that may or may not be beneficial to have, but are not as clearly necessary as the mandatory requirements to collaborate. Typical examples involve the amount of additional information gained by collaboration, but having unclear value to influence a decision, nor its quality. Furthermore, the cost and effort to obtain those additional opinions, or preferences, priorities, etc. may even complicate the decision and damage the entire decision process.

To evaluate the advantages and limits of collaboration for decision support in the context of CCT, five key metrics can be considered:

1. *Decision quality* – quality of the decisions being made now; of future decisions

2. *Information availability* – what information is required and when; what information is not required; what additional information can add benefit to the decision making process and to the decisions' quality.

3. *Timely completion* – Which decisions have to be made, and by when.

4. *Multiple views* – What level of diversity of logic and of motivations are beneficial; negotiated decisions; visibility of the decision process and the decisions made; co-insight, the ability to avail and gain timely collaborative insights of the multiple participants, including overcoming adversarial attitudes.

5. *Multiple engagement* – For a CDSS to be useful and effective, the collaborating participants may or may not need to be engaged during (or during part of) the decision making process, at the decision taking stage, and during (or during part of) the implementation and revisions of the decisions.

These five metrics are interrelated and influence each other. They will be considered in the case studies described later in this article. There are other metrics that can be considered (e.g., see [11], [12], [13], [16], [19]).

3 CCT augmentation to overcome collaboration limits and risks

CCT has been developed, validated and implemented by researchers and engineers worldwide. Its main purpose is to understand, design and optimize collaboration support systems, collaboration protocols, and collaboration algorithms that can augment all aspects of collaboration. Despite the potential risks and failures inherent in complex interactions

Table 1. Characteristics of DSS and CDSS and their role in augmenting collaboration (Source: [19]; adapted from [23])

Type	Functions
Knowledge repository	★ Identify and solve problems ❖ Facilitate interactions among decision-makers ➢ Define, document, and regulate the actions of decision-makers ★ ❖ ➢ Private repositories under the access control of individuals ★ ❖ ➢ Public repositories; shared access and share knowledge
Requests	❖ Customize requests based on specific needs ★ Enhance flexibility in timing of requests
Operations	★ Provide knowledge to meet unanticipated demands ★ Generate knowledge via automated calculation/analysis/reasoning
Presentation	❖ Customized presentation of results based on specific needs
Coordination	❖ Facilitate internal/external communication among decision-makers ➢ Structure and regulate individual/group decision-making tasks ➢ Structure and regulate interrelated decisions

❖ Characteristics to support communication among decision-makers
★ Characteristics to support knowledge for decision-making
➢ Characteristics to support decision-making processes

associated with collaboration (Table 2), augmentation by CCT has been developed to overcome them.

As it is shown in Figure 1, cyber support is integrated with common CDSS (Figure 1a), but in addition, cyber support with CCT-augmentation of collaboration processes (Figure 1b) can and is designed to overcome the risks and shortcomings of collaboration processes and systems.

A brief summary of CCT ([35]) is provided in Table 3. CCT comprises seven augmentation principles, listed in the first column. For each of them, its role, collaborative decisions, and examples of collaboration augmentation models, protocols, and algorithms developed to implement it are shown in the last column. One can find details about each of them in the references of Table 3.

The CCT augmentation roles of each principle and its related cyber tools are as follows.

CRP: Collaboration Requirement Planning. It includes advanced

Table 2. Decision making by CDSS based on collaboration among participants

<table>
<tr><th>Decision making participants</th><th>Decision examples</th><th>Risks of Collaborative Decisions</th></tr>
<tr><td>People</td><td>Investments;
policies;
budgeting;
responses;
resource allocation;
scheduling</td><td rowspan="8">- Low or no incentive to collaborate

- Potential logic errors

- Potential conflicts

- Wrong/missing data

- Costs of collaboration

- Delays

- Poor or no compromise

- Too late for some or all

- Too early for some or all

- Other mismatch challenges</td></tr>
<tr><td>People and machines</td><td>Activation;
recovery;
diagnostics</td></tr>
<tr><td>Software agents</td><td>Simulations;
calculations;
assembly design;
service planning</td></tr>
<tr><td>People-machines-agents</td><td>Coordination;
priorities;
healthcare action alternatives</td></tr>
<tr><td>Robots-Robots</td><td>Navigation;
monitoring;
co-assembly</td></tr>
<tr><td>Swarms of robots, drones</td><td>Surface treatment;
rescue;
exploration;
security</td></tr>
<tr><td>Sensors</td><td>Health of crops;
safety;
assessment and prediction of conditions</td></tr>
<tr><td>Combinations changing over time</td><td>Above decision combinations</td></tr>
</table>

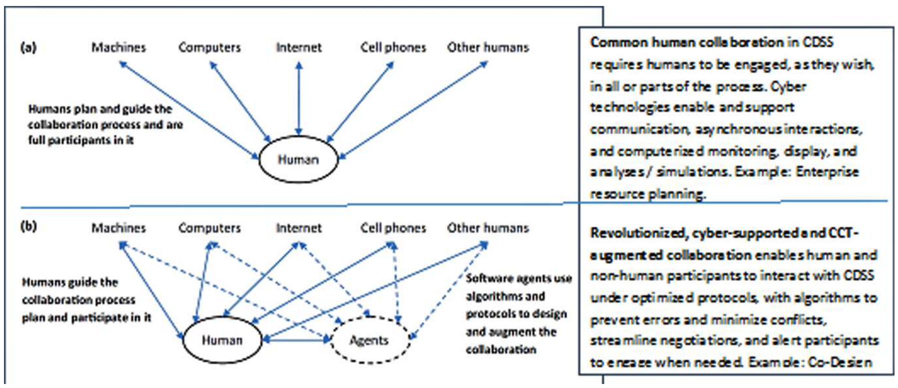

Figure 1. CDSS collaboration with: (a) Cyber support; (b) Cyber support and CCT augmentation (Source: [38])

pre-planning (CRP-I), followed by on-going monitoring and adaptive control/re-planning of collaborating resources (CRP-II). The algorithms, protocols, and multi-agent systems for CRP are designed to create and gain collaborative intelligence (CI) from multiple human and non-human participants for the collaborative decisions. By pre-planning and re-planning the collaboration, there is a greater chance to eliminate gaps and inefficiencies, thus improving the quality of collaboration process and of their outcomes.

EWP: e-Work Parallelism. It implies optimally exploiting the fact that work in cyber workspaces and workflows, and in human workspaces and workflows can and must be allowed to advance in parallel, and should not bottleneck each other. For decision support, it implies that cyber tools, hardware and software agents, can operate at their own speed and in parallel to human decision makers, to prepare, acquire, exchange, analyze, evaluate, an even recommend decisions in support of human decision makers and decisions.

ECR: Errors and Conflicts Resolution. Eliminate or minimize the cost of resolving conflicts among collaborating e-workers and cyber tools by automated, cyber-supported error and conflict detection, prognostics, and prevention systems. Without it, complex, large scale decision systems based only on human-interaction will collapse, as has been proven theoretically and empirically.

CFT: Collaborative Fault Tolerance. Cyber tools, protocols, algorithms, and agent systems are designed to improve the performance results of a team, including team decisions, such that a team of weak collaborators can together reach better results than a single, non-team and even flawless agent.

A-D: Associate-Dissociate (also known as JLR, Join-Leave-Remain). Cyber tools designed under this principle include collaborative control decisions on when, whether, and why to associate, or dissociate from a team, or network, of collaborators, based on on-going cost/benefit evaluations. This evaluations are conducted in parallel to the collaborative network performance. For collaborating decision makers, for instance, it means that some of them (e.g., sensors, knowledge bases, etc.) may or may not need to be engaged in certain portions of a decision process but join later. Or it could mean that for a team of decision makers, they may find out that one or a few of them (e.g., certain robots, or drones, or humans) can be disengaged from the team, at least for a certain period, to eliminate damage in future decisions, or in certain decisions.

ELOCC: Evolutionary Lines of Collaboration and Command. This CCT principle guides the development of evolutionary and machine-learning cyber mechanisms for organizational learning and improvement of both ad-hoc decisions improvisation, on the spot self-reorganization and contact creation, and best matching protocols (BMP), for pairing suppliers (providers) and consumes (clients). For decision support, it implies the same, with emphasis on the evolutionary nature of decisions over time.

BMP: Best Matching Protocols were originally developed as part of ELOCC, and later also as part of all other CCT principles. They are shown in Table 3 under ELOCC and CRP. Their objective is to optimally match sets, either by pairing best analytic tools and agents to given decision requirements, or matching higher dimensional sets of sensors, robots, instruments, and given planning and control decisions ([31]).

BIC: Bio Inspired Collaboration. These are cyber tools, protocols and algorithms designed to increase the collaborative intelligence (CI), hence the resulting benefits of collaborative decisions and control, by bio inspired and socio inspired collaboration mechanisms observed in nature, e.g., genetic algorithms, ant and other colony protocols and algorithms, and market negotiation games.

CSCW oriented protocols

A major objective in CDSS is to understand and deliver interaction protocols that would structure and improve collaboration processes and the resulting decisions' quality. Protocols of collaboration in CDSS ([19], [41]) include interaction protocols developed extensively by researchers in the area of CSCW, Computer Supported Collaborative Work. Their focus is on social, human factors and psychological aspects of computer supported collaboration. Mostly, they are concerned with the collaboration shown in Figure 1a, and can provide guidance to cyber-supported collaboration shown in Figure 1b.

Steps of collaboration that are addressed by the CSCW protocols are identified as Generate, Reduce, Clarify, Organize, Evaluate, and Build Consensus (e.g., [27]). Typical functions followed by these protocols are:

- Voting methods (e.g., [14], [20])
- Information sharing (e.g., [9])
- Argumentation by groups (e.g., [43])
- Resource sharing and allocation (e.g., [1], [45])
- Mediation and interaction (e.g., [21])
- Crowd sourcing (e.g., [2],[10])

An example of a systematic support system for CDSS to enable collaboration is Thinklet ([3], [17], [22]). Additional details on CSCW oriented protocols can be found in [41]. Several researchers have studied their complexity, e.g., [20, 21].

While the CSCW collaboration and interaction protocols have advanced collaborative decision systems ability by providing protocols for functional collaboration, the CCT augmentation protocols differ in two main aspects:

1. They seek to automate and alleviate known risks and limitations that are typical in computer supported collaborative interactions, as described above and further below.

2. In addition, CCT assumes that any decision system involves, beyond human decision makers and knowledge bases also sensors, robots, and software agents, who may need to make their own decisions autonomously, as well as interact with humans for their decisions

CCT augmentation Protocols

As discussed above and shown in Table 3, the CCT augmentation protocols are designed as cyber-based augmentation of collaborative interactions. They are focused on solving the following typical risks in collaborative interactions:

- Inefficient, ineffective decision processes due to overloaded decision makers and lack of common, workflow based decision process plans. These risks are addressed by the CRP protocols (e.g., [59])

- Unclear assignment of who does what and when in support of the decision interactions. These risks are addressed by the EWP protocols (e.g., [7])

- Errors and conflicts encountered during collaboration, requiring monitoring and detection, and either recovery to overcome them, or better yet, machine learning to prevent and eliminate them. These risks are addressed by the ECR protocols (e.g., [8], [24], [28])

- Errors and conflicts which cannot be resolved, or can only be resolved too late, pose risks to collaboration. Such risks require fault tolerance mechanisms designed in the support systems, and are provided by the CFT protocols (e.g., [25])
- Not all humans, robots, agents, sensors, need to be engaged throughout the entire decision process. On the other hand, they may be needed as active and engaged participants at certain times, weather preferred by them or needed by other participants. For instance, in such case they should be alerted for active participation when needed. Handling this concern is by the AD protocols (e.g., [53])
- Certain participants may or may not be available when they need to or are invited to participate actively. These risks are addressed by the ELOCC protocols ([52], [58])

Examples of the design implementation and applications of the CCT augmentation protocols are given, for example, by [39] in manufacturing and logistics; [36] and [47] in modeling and decision support for sustainability; [26] and [37]in the design of service tasks administration protocols; [46] in complex production facility collaborative management; and [51] in security of supply networks. In many of these research applications, humans are in the loop as collaborating decision makers, including robots, sensors, and software agents. In some of these research applications, only autonomous robots, sensors, and software agents are collaborating to make their own autonomous decisions.

The impact and benefits gained by applying the above CCT augmentation cyber tools are intuitive, as they address directly solutions to critical and common weaknesses of collaboration in CDSS. These impacts and benefits have also been modeled, measured, and validated by researchers, based on the above five metrics and other metrics.

Table 3: CCT principles and PRISM Center discoveries of CCT collaboration augmentation cyber tools developed for them (Source: [30], [61]; Adapted from [35], [38])

Principle* – Rationale	Features	Applied decisions	e-Mfg/e-Service decisión areas	Model/ Algorithm/ Protocol**
CRP-I & CRP-II *"Think before you act"*	Collaboration planning & interaction	Resource planning	Multi-robotic assembly; Multi-processors	CRP; TAP; BMP
	Multi-agent design	Agent theory	Mfg operations	ABMS
EWP *"Divide and conquer"*	Collaboration protocol design	Telecommunication, adaptive, and exchange protocols	ERP applications; Electronic inspection/testing; Wireless Micro-Electro Mechanical Systems (MEMS); Mfg networks	TIE/P; Test-LAN; TIF; BMP; TAP
	Middleware protocols	Client-server models	Automotive electronics; Flexible assembly	RAP; TOP
	Parallelism	Parallel/grid computing	Global design/mfg; Collaborative decision-making	DPIEM; TAP

Continuation of Table 3

Principle* – Rationale	Features	Applied decisions	e-Mfg/e-Service decisión areas	Model/ Algorithm/ Protocol**
	Resource & task allocation	Local area networks; Internet	Electronic assembly & test; Global mfg networks	TestLAN; MEN; TAP
ECR *"Learn from mistakes"*	Synchronization/ Re-synchronization	Agent theory	Robotic maintenance	ServSim
	Information assurance	Total quality management	Agent-based mfg/service	MERP
	Error detection & prevention	Computer recovery; Multi-agent systems	Robotic assembly; Multi-robot systems	NEFUSER; EDPA; CEDP
CFT *"Team for synergy"*	Fault-tolerant integration	Sensor fusion	Flow MEMS sensors; Wireless MEMS sensors	FTTP; TIE/ MEMS
	Conflict resolution	Telecommunication; Co-assembly	Co-facility design; Multi-robot systems; Assembly/disassembly	FDL; FDL-CR; CRP; BMP

Continuation of Table 3

Principle* – Rationale	Features	Applied decisions	e-Mfg/e-Service decisión areas	Model/ Algorithm/ Protocol**
AD *"Be selective"*	Enterprise integration	Network flow	Distributed & networked mfg/service systems	MEN Opt.; JLR; BMP; CD-CSP; TAP
	Organizational learning	Enterprise computing	Mfg/assembly corp.	CMS
ELOCC *"Trust the backup"*	Workflow integration & harmonization	Data flow; Distributed database; Workflow protocols	Aerospace mfg; CIM	DFI; DAF-Net & AIMIS; BMP; TAP
	Information sharing & collaboration	Virtual environments; Task graphs; Network computing; Internet/Intranet	Mfg cells; Distributed designers; Mfg networks; e-Business/e-Service	FDL; IDM; Co-X Tools; T-C-M; TAP

Continuation of Table 3

Principle* – Rationale	Features	Applied decisions	e-Mfg/e-Service decisión areas	Model/ Algorithm/ Protocol**
	e-Learning/ e-Training	Learning theory; Distributed & collaborative DSS	ERP applications; Emergency response	MERP/C; TSTP
	Viability measures	Virtual mfg	HCI	TIE/A
	e-Work scalability	Distributed computers	Mfg networks	MEN Opt.
BIC *"Follow nature"*	Distributed optimization & control	Agent theory; HMS; Swarm intelligence; Evolutionary algorithms	Mfg process planning & scheduling; Intelligent shop floor control; Collaborative mfg/service processes	GA; AS; NN
	Evolution	Emergent networks; Neural networks; Evolutionary & adaptive behaviors/ patterns in nature	Evolutionary robotics; Mfg networks; Negotiation systems; Self-formation & self-evolution of emergent networks	GA; AS; NN

* CRP: Collaboration Requirement Planning; EWP: e-Work Parallelism; ECR: Error and Conflict Resolution; CFT: Collaborative Fault Tolerance; AD: Association-Dissociation; ELOCC: Emergent Lines of Collaboration and Command; BIC: Bio-Inspired Collaboration; BMP: Best Matching Protocol

** These models, protocols, and algorithms are described in detail in the table references

4 Collaborative Intelligence (CI) by CCT augmentation of CDSS

Two CCT-based developments augmenting collaboration in CDSS are the Co-Insight system, and the Collaborative Intelligence (CI) of participants. Recent research has shown that both help understand better the collaborative decision and control process, and enable reaching better quality decisions (e.g., [15], [60] [61]).

Research on acquiring and accumulating intelligence has been conducted by many researchers (e.g., [32], [40], [44], [55]). See a summary in Table 4.

CCT augmentation of collaborative decisions by the Co-Insight framework is shown in Figure 2. It is designed to enable multiple participants to engage in information and knowledge exchange in a way that incorporates visual analytics through knowledge repositories and exchange protocols. The unique advantage of this framework is that it is built with CCT cyber tools. A Co-Net, a collaborative network of decision participants, enables interactions under best matching protocol of participants, recommending who should be involved at each period of time. The recommendations are generated through a collaborative network optimization protocol (CNO). Another best matching protocol guides the matching of decision analytics tools that are best suitable for each given decision or decision stage.

The Co-Insight framework is developed on a HUB, a powerful computational infrastructure (e.g., Industrial Internet of Things/Internet of Services, or cloud computing) to enable large scale, decentralized interactions for a small social/group network, or for a wide network of participants.

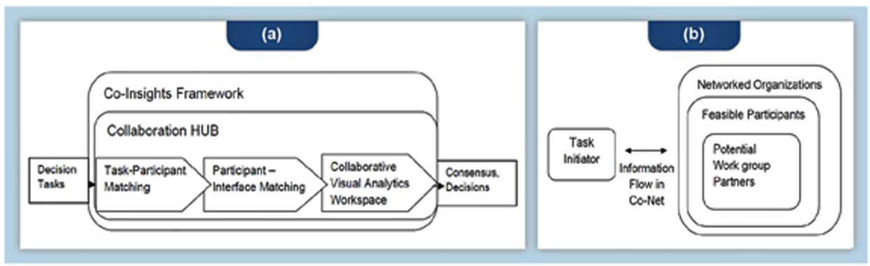

Figure 2. CCT augmentation of collaborative decisions by Co-Insight: (a) The Co-Insight framework with task-participant matching (deciding with whom to collaborate for a specific decision problem); participant-interface matching (deciding which tool to apply for a specific decision analysis); within a collaborative, visual analytics workspace. (b) The role of participating collaborators in a Co-Net for Co-Insight. (Source: [60])

Research has shown that building and augmenting the CI of participants in cyber-physical systems and in CDSS can provide better support for achieving both their individual and their common, organizational objectives. A definition and formal quantitative measure of CI have been developed ([61]). They are based on the definitions of the two key elements, collaboration and intelligence. Three recent case studies of collaborative decision support systems have been analyzed relative to their formal level of CI. The three cases involve limited, though non-finite groups of collaborating human and non-human entities.

Case 1. Collaborative Design

Telerobot-enabled, computer supported collaborative design under CLM, collaborative life-cycle management, was modeled and experimentally studied in a lab. Novice and experienced designers collaborated over a HUB with CAD systems, CAE systems, control software development, and a remote robot to collaboratively design and test

Table 4. Interactions impacting intelligence to improve decision processes and decisions quality features (Source: [61]; adapted from [15])

Type	Definition	Methods	Benefits	Example
Communication intelligence	The ability to communicate between humans, machines, and human - machine systems	Effectively communicate between multiple entities	Increase communication efficiency, and reduce cost and time	Negotiation and making contracts between business partners; process outsourcing
Cumulative intelligence	The ability to accumulate knowledge and form a base for decision-making	Make decisions based on present state and also previous states	Identify positive and negative strategies from historical data	Research activities (standing on the shoulders of giants)
Cooperative intelligence	The ability to deal with cooperation among multiple partners	Prevent conflicts during real time parallel execution	Reduce down time and interruptions due to conflicting actions	Concurrent assembly operations along a conveyor
Collective intelligence	The ability to integrate intelligence from a group/organization and to act, even approximately, as a single, rational agent	Collect and combine knowledge from disparate sources	Increase the probability of better decisions	Trade promotions suggestions for client and customer
CI, Collaborative Intelligence	The ability of an entity or a group to collaborate well with others	Collaborate towards a set of common goals while keeping autonomy	Streamline the workflow of information and operations for overall welfare	Between knowledge intensive clients and e-Service providers; between retailers, manufactures & suppliers (Nestle, Wal-Mart)

an electronic assembly. The decisions they made throughout the experiments with and without CCT augmentation were evaluated. The level of CI in the experiments was measured and evaluated. Metrics of improved collaboration and improved quality of design decisions were analyzed (e.g., [57]).

Case 2. Supply Network Control

Collaborative product line control in a global supply network of paper and related products was designed based on CCT augmentation of the decision support. Certain decisions were automated for real-time alerts, batch order rescheduling and resequencing, and feedforward process control adjustments. Selectively, some of these control decisions were escalated to human-in-the-loop supervisors. Performance metrics of decision and control processes, of their CI, and decision and control impact on production quality were analyzed and evaluated (e.g., [46]).

Case 3. Demand and Capacity Sharing

Collaborating enterprises can benefit from sharing demands for their products and services, and supply capacities that are available to them. On-going negotiations and interactions about such sharing between those that have, from time to time, excess unused capacity, or temporary decline in demand, can yield significant mutual advantages. For instance, airlines sharing their equipment and passengers dynamically ("code sharing"), and automotive suppliers, one having excess storage capacity, while another is having surplus of unsold vehicles and lacking storage space. Such demand and capacity sharing decisions were designed with CCT augmentation, and the level of CI and corresponding decisions' quality and decision process metrics were evaluated (e.g., [29], [48], [53]).

The five collaboration metrics were assessed in the above three cases, and overall observations are summarized in Table 5. Based on these observations, the benefits based on these metrics have been measured and shown with statistical significant to yield advantages when a higher formal levels of CI are enabled as shown.

Table 5: Measured impacts of the formal level of CI on key CDSS metrics (Source: [38], [61])

Collaboration Metrics	*Case 1. Collaborative Design*	*Case 2. Supply Network Control*	*Case 3. Demand-Capacity Sharing*
Decisions quality, service level, effectiveness, stability	- Improved design quality - Improved design robustness	- Lower throughput variability - Reduced work-in-progress	- Improved stability of interactions - Improved stability of integration decisions
Information availability	Improved through Co-Insight	Improved through Co-Insight	Improved through Co-Insight
Timely completion	Less time to complete design tasks	- Increased throughput - Reduced work-in-progress	- Improved resource utilization - Reduced cost of mismatch
Multiple views	Enabled through Co-Insight	Enabled through Co-Insight	Enabled through Co-Insight

Continuation of Table 5

Collaboration Metrics	*Case 1. Collaborative Design*	*Case 2. Supply Network Control*	*Case 3. Demand-Capacity Sharing*
Multiple engagement	Embedded on HUB-CI with decision support alerts	- Automatic engagement as needed of sensors and knowledge-bases - Alert-based interactions with line supervisors as needed	- Automatic engagement as needed of sensors and knowledge-bases - Alert-based interactions with enterprise agents and supervisors as needed
Cost of Collaboration	Errors and conflicts removed at earlier stages of design	Minimized impact of disruptions	Reduced cost of mismatch

5 Conclusions

For CDSS, Collaborative Decision Support Systems to function effectively and to deliver high quality decisions over time, effective collaboration support is essential ([19]). In this article, the contributing power of CCT, the Collaborative Control Theory and its associated cyber tools to augment collaboration ([38]) by multiple decision participants are explored. Beyond traditional CSCW protocols and methods, that address mostly human decision makers, CCT augmentation of collaboration incorporated multiple human decision makers and multiple software and hardware agents, sensors, robots, and other automated instruments.

The design principles of CCT and their associated collaboration protocols are discussed, with their specific contributions to solve and alleviate risks and weaknesses common in collaboration for CDSS. The CCT-based Co-Insight framework and Collaborative Intelligence (CI) are presented as additional major components that can improve and enable productive and effective CDSS.

Three case studies implementing CTT principles, protocols, and Co-Insight are described based on recent research on the correlation between CI and its impacts on decision process and decision quality. According to these case studies and research results, the correlation is positive, meaning that with greater levels of CI along time, better decision processes and decisions quality can be gained. In addition, this research has provided experimental methods that are available for further research as follows.

While it can be intuitive that higher levels of collaboration and higher levels of CI can lead to better performance based on better decisions, it is still necessary to establish the limits and appropriate levels that are optimal, or best in terms of cost and benefits. Specifically:

1. What are the best ways to create, foster, adaptively adjust, and sustain collaboration processes and level of resulting CI throughout the lifecycle of given decision support systems and the systems those decisions are meant to optimize?

2. It has been proven that optimal performance of the CDSS is typically attained with optimal but selective levels of collaboration and of CI; what are the ways to simplify and optimize, not maximize those levels?

Future research in these directions is anticipated by the CDSS, CSCW, and CCT communities. And already CDSS are implemented and positively influencing large scale, connected enterprises and cyber physical infrastructure and networks.

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