A Framework for Distributed Situated Decision Support

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Abstract

Centralized decision making is becoming inadequate in many business domains, which are inherently dynamic and complex. In light of these considerations the distributed computing paradigm is gaining substantial support and attention. Investigation of new models for distributed decision support systems is an important direction of research. In this work we are aiming to build upon the recently introduced model for situated Decision Support Systems to address distributed and coordinated decision support. To demonstrate the applicability of this framework, a prototypical application for lead time management has been implemented. Simulation experiments have been conducted to investigate the impacts of real-time information and information coordination on decision performance. Overall, the results support our expectation that both information delay and information coordination have significant impacts on decision performance.

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1. Introduction

Effective decision making and decision implementation in today's business world is becoming increasingly complex due to increased market competition, overwhelming information, demanding and dynamic customer base, unstable political environments, and many other uncertain factors. This complexity makes centralized decision making difficult or even impossible in many domains due to the limited cognitive capacities of human decision makers. Thus, in many cases people have to combine individual information processing capacities to tackle complex business problems. Consequently, decision making is often distributed over empowered employees within an organization as well as over suppliers and/or customers across organizations as evidenced by emerging business practices such as decentralization, customerization [30] and supply chain management [5].

This phenomenon of distributed decision making (DDM) can be defined as a process involving one or more interdependent decision units that have compatible or incompatible decision goals. The decision units consist of either human beings or machines or, more frequently, some combination of them. This definition is very general in that it can potentially include every kind of decision making process except one-time individual decision making. In fact, group decision making, organizational group making, and negotiation can be viewed as special cases of DDM.

Decision Support Systems have been traditionally proposed as the means of complementing human judgment with computational models, data, and knowledge repositories to enhance decision making effectiveness. In particular, various types of DSS accommodating multiple decision makers include Group Decision Support Systems (GDSS) [2,12], Organizational Decision Support Systems (ODSS) [1,17], and Negotiation Support Systems (NSS) [13].

Modern effective decision making has to focus on timely information processing, situation assessment and decision and action generation in a dynamic fashion [9,27]. A novel model of decision support should explicitly focus on being able to capture required information in time and implement decision makers' decisions in most direct and immediate way possible. This demand for dynamic decision making support is signified by the emergence of and growing interest in research on real-time DSS [26] and "situated" DSS [28].

This paper aims at proposing new DSS framework that facilitates development of flexible systems to support dynamic distributed decision making. The framework is an extension of a recently introduced situated DSS model [28].

2. Distributed Decision Making Section Title

The process of distributed problem solving/decision making involves decomposition of a complex problem/decision into a set of subproblems/subdecisions. The decomposition itself is a problem that has to be tackled to obtain an efficient and effective decision structure. In fact, this decomposition is a meta-decision making process that determines "who can decide what". The purpose of distributed decision support systems (DDSS) is to improve the effectiveness of decision units and facilitate the coordination among them.

We use the term “Decision Making Systems” to refer both to DSS as well as autonomous systems. A decision unit DU is an entity that carries out decision making process DM. It involves at least one decision maker, who may be a human or not. We further define a decision making system (DMS) as a system including at least one decision unit. Distributed decision making systems (DDMS) are special cases of decision making systems (DMS) that consist of at least two decision units. Thus, a natural way to classify DDMS is to categorize them by the types of decision and coordination. We can broadly consider three types of coordination. The first one is *No Coordination* referring to the systems in which multiple units do not interact with each other. They do not share any information and, thus their respective decision systems are effectively stand-alone. The second type of coordination, *Cooperation,* refers to the systems in which units interact with each other to achieve a common goal or conflict-free goals. The last type of coordination, *Competitive*, enables organizations with competitive goals to achieve compromise or some other sort of conflict resolution.

Based on Thompson’s concept of the relationship between technology and organizational structure Kumar and van Dissel [19] have proposed a typology for Inter-organizational systems (IOS), which is relevant to our study. The simplest one is pooled information resource IOS, which corresponds to pooled interdependency relationship. By means of this type of IOS, a group of organizations can share common IS/IT resources and they have minimal potential conflicts. The second type of IOS is value/supply-chain IOS. It corresponds to sequential interdependence relationships, where output from one organization serves as an input to another organization. EDI is a typical application of this type of IOS. Most of current supply chain management practices, such as collaborative demand management, belong to this category. The most complicated type of IOS is networked IOS by which organizations often obtain input from and deliver output to others interactively. Their interdependencies are reciprocal and might lead to a high level of potential conflicts.

Based on the above, we can highlight six types of relationships: 1) *Independent*, i.e. each decision unit makes its own decision without considering the other decision units; 2) *Cooperation with Pooled interdependence*, where two and more decision units have non-conflicting goals and share common IS/IT resources; 3) *Cooperation with Sequential interdependence,* where one decision unit makes a part of a decision and then passes it to the other decision units; 4) *Cooperation with Reciprocal interdependence,* where two and more decision units have non-conflicting goals and engage in frequent communications; 5) *Competition with Pooled interdependence*, which refers that two and more decision units have conflicting goals but share common IS/IT resources; and 6) *Competition with Reciprocal interdependence,* which usually involves negotiations among various decision units with conflicting goals.

3. Distributed Decision Support

Eom’s review of DSS research covering the period from 1970 to 1999 [6] shows that distributed decision making has been somewhat underinvestigated by researchers, though there have been significant efforts focusing on related systems, including group decision support systems (GDSS), organizational decision support systems (ODSS) and negotiation support systems (NSS). In the discussion of past, present, and future of decision support technology, Shim et al. [23] pay little attention to DDSS when they discuss collaborative support systems. This lack of research on DDSS could be attributed to the ambiguity of DDSS concept itself.

The term Distributed DSS, originally introduced by Scher [21], referred to a conference-based system in an organization. Rathwell & Burns define a DDM system as a cooperative network facilitating communication and conflict resolution among equal decision makers [20].

Swanson treats DDSS as one perspective of organizational DSS [24]. He further identifies the domain of DDSS, which is characterized by semi-structured decision model and semi-determined decision criteria, by comparing distributed decision support with distributed computing and distributed communication. Based on Swanson's definition of ODSS, Chung et al. state that distributed decision support system (DDSS), conceived as a network of decision making nodes in an organization, is a subset of ODSS [4]. In addition, they divide DDSS into two categories: Rigid DDSS and Flexible DDSS.

Other researchers have devised various technical approaches to build DDSS. Chi and Turban proposed to use agents for distributed resources, such as knowledge base and DBMS, to support executive decision making [3]. Jeusfeld and Bui [14] proposed a script language to allow construction of DSS from components stored on various Internet sites [14]. Ju et al. proposed an agent-based architecture of DDSS and discussed how the agents coordinate to largely automate decision making [15]. Gachet discussed a decentralized technical architecture for distributed DSS [7]. Gachet and Haettenschwiler conducted a case study to identify the impact of single-user DSS vs. distributed DSS in the collective decision making process [8].

Based on past work, we find that the traditional view of DDSS is either too narrow to cover some important aspects of distributed decision making process, for example, the peer-to-peer relationship between two decision units, or too technical to consider the nature of distributed decision making process, i.e. the interdependence of preference structures of decision units, which could be dynamic and uncertain.

To bring together diverse research on DDM from different disciplines including computer science, economics, organizational theory, psychology, and many others, Schneeweiss proposes a unified model of distributed decision making characterizing it as the design and coordination of connected decisions [22]. In this work, a decision model includes a set of decision criteria C, action space A, and status of information I. In its simplest form, decision making is distributed over two decision units. If these two units have an identical decision model, i.e. sharing same decision criteria, action space, and information, we may say that they are in perfect cooperation. On the contrary, if their decision models are completely different, they are in fact isolated from each other. Usually the relationship between two units is somewhere between these two extreme situations.

Situated Decision Support Systems

Vahidov and Kersten argued that traditional DSS research ignored implementation and monitoring phases of decision making process [28]. According to them, systems built around traditional DSS concept, i.e. Simon's intelligence-design-choice model, are disconnected from their respective problem domains. Inspired by software agent technologies and research on active DSS, they proposed a new framework of DSS called "Situated DSS", or "Decision Station" architecture, which promotes close links with the problem environment and has capabilities to implement decisions through the "effectors" as well as monitor the change of problem environment by means of "sensors".

Sensors and effectors are key components that differentiate situated DSS from traditional "standalone" DSS. They can be equipped with passive capabilities, such as connecting, transforming, querying and alerting users, and/or active capabilities, such as adapting and planning. Additionally, the framework contains active user interface and DSS kernel. The latter includes data, models, and knowledge, as well as the active manager that performs the task of monitoring and has limited authority for autonomous action. The advantage of this architecture is that it can provide human decision makers with timely and proactive decision support in dynamic and complex environment.

While this framework promises to improve efficiency and effectiveness of decision making for single decision maker, it does not consider the issue of distributed decision making. In our view, it would be beneficial to extend this framework to handle distributed decision making in the increasingly complicated business environment of today. Distributed decision support based on the ideas of situatedness and proactiveness, while preserving human involvement could be an adequate response for the prevailing trends in modern decision making.

4. Distributed Situated Decision Support Model

Coordination is the key element in any type of distributed system. To accommodate the design of DSS, we need to identify the key components of information exchanged between the units. Kim et al. present four kinds of inputs and outputs of a model when designing a model coordination subsystem for organizational decision support systems [16]. Based on their ideas, we divide information into four categories (in case of two DUs): $I = \{I^L, I^S, I^C, I^R\}$, where I^L represents local information of a DU, I^S represents the commonly shared information between DUs, I^C is the control information from other DU, and I^R is the feedback information from the other DU. When a DU receives control information, it can do nothing but follow this information in its decision making process. On the contrary, the feedback information I^R may be either considered for generating control information or dropped during the interaction. Compared with I^L and I^S, which are relatively stable, I^C and I^R are dependent upon the interaction between two units.

Considering that information asymmetry is more popular than information symmetry, Schneeweiss defines one DU as top level and the other one as base model. We tend to treat two levels equally, i.e. by default there is no hierarchy between the units [22]. This structure is shown in figure 1 with the decomposition of information status *I*.

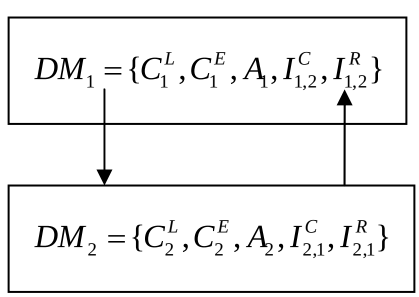

Figure 1. Interactions between decision models

Here C_1^L refers to private criteria of top level, while C_1^E stands for representation of base-level preferences and vice versa. The constitution of criterion C determines how a DU treats the other unit. For example, if $C_1^E = \varnothing$, it means that top-level decision maker is egocentric; if $C_1^L = \varnothing$ then he/she/it is altruistic. Normally, these criteria are not null. It means that each DU considers its own criteria as well as those of the other unit.

Based on the decomposition of criteria structure, we can arrive at six styles of coordination between two decision units, listed in table 1. In this table, 0 stands for an empty set and 1 stands for a nonempty set. For example, regarding coordination style 1, the local criteria of both decision units are empty, but their external criteria are not empty.

Table 1. Coordination styles.

Style of Coordination	C_1^L	C_1^E	C_2^L	C_2^E	Description
1	0	1	0	1	Both DM_1 and DM_2 are altruistic (consider the other's preference only)
2	0	1	1	0	DM_1 considers the other's preference only while DM_2 consider itself only.
3	0	1	1	1	DM_1 considers the other's preference only while DM_2 considers both.
4	1	0	1	0	Both DM_1 and DM_2 are egocentric (consider their own preferences only)
5	1	0	1	1	DM_1 considers its own preference only while DM_2 considers both.
6	1	1	1	1	Both DM_1 and DM_2 consider their preferences as well as the others' preferences.

With regard to information sharing, we can obtain eight types of information coordination. If we consider the above schemas together, we will get 6 × 8 = 48 scenarios of distributed decision making from information processing perspective.

To illustrate the above concept, a typical model with three integrated decision stations is presented in figure 1. The coordination between the top-level DS and base-level DSs is planning process, which is enabled by control information flow and feedback information flow.

The coordination between two base-level DSs is negotiation process enabled by the exchange of feedback information (Local and shared information are ignored in this figure).

5. Distributed Decision Stations for Lead Time Management

5.1 Lead Time Management

During the past decade, the increasing popularity of the Internet has promoted many manufacturing companies to adopt e-commerce business model, which enables them to directly interact with end consumers by eliminating costly intermediaries in the traditional supply chain. Correspondingly, their business philosophy has shifted from production-centric strategy to customer-centric strategy. This, in turn prompts the shift from mass production, to mass customization, and even to "customerization" [30], an effort to integrate customer into internal business processes, such as collaborative product design. In mass production model products are usually made to stock (MTS) according to sale forecasts, whereas in mass customization model products are made to actual customer orders (MTO). As a result, MTO companies can enjoy the benefits of product flexibility and lower inventory cost, but at the same time they might suffer from a longer and unstable order-to-delivery (OTD) lead time.

According to input-process-output model, production can be treated as a transformation process that employs various resources, such as machine and labor, to convert raw materials into final products [18]. Workload control (WLC), a concept first introduced by Wight [29], is aimed at maintaining transformation time at a normal level by controlling input/output. Conceptually, workload is modeled as a queue where work is waiting to be processed at a certain resource. As a whole, a production system can be modeled as a queuing network, and hence a computational solution is hardly feasible [10].

The main purpose of workload control is to manage lead time. Though WLC concept is originally devised to handle lead time in manufacturing process, it has been extended to the whole process of order to delivery (OTD) cycle. In his formal analysis of workload control model, Kingsman identified four phases of order fulfillment process in MTO companies, and pointed out four corresponding levels of workload control, i.e. customer inquiry, order acceptance, job release, and priority dispatching [18].

Though WLC is conceptually simple in concept and has important implications for the practice, the actual implementation of the mechanism is far from trivial.

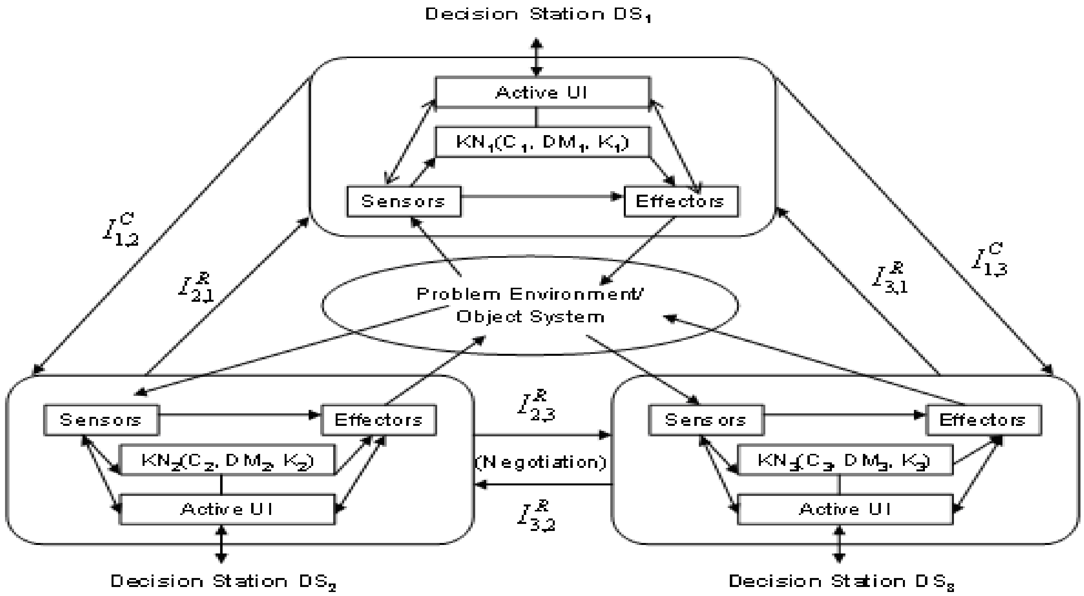

Figure 1. Three Distributed Decision Stations

5.2 Business Case

A fictitious web-based make-to-order manufacturing company is considered here to implement lead time management using work load control concept. The sales orders of the company primarily come from the e-customers. Order arrivals are random and the intervals between them are highly varied. Moreover, the company allows its customers to personalize products and, thus production processing time of each order is also varied with the specific product configuration. These characteristics seem best fit the application of WLC concept [11].

We assume that firms employ just-in-time production philosophy, i.e. their supplier can deliver required materials without delays. Hence, the waiting time for materials can be ignored in our model. In addition, we assume that total manufacturing lead time T_m is relatively small due to the high efficiency of manufacturing and that the default scheduling rule is first-in-first-out (FIFO). Under these assumptions, the total order-to-delivery (OTD) lead time is largely dependent on the waiting time in order pool T_w. Thus the management of OTD lead time is highly determined by the management of order pool size.

The stable size of order pool can be maintained by adjusting demand and/or production capacity. In this company, a demand/capacity planner is assigned to coordinate marketing and production department and has a final say on demand and production management to ensure a good customer service level while keeping down marketing expenses and/or production cost.

To provide customers with more flexibility, the company conceives a new idea that customers not only can track order but also can schedule orders by themselves if they want (customerization). The principle is that customers can switch their positions in the order pool by negotiating a corresponding compensation. As a consequence, a customer can get his/her order processed earlier if this person is willing to pay a certain amount of money to the other customer. By combining work load control and customer self-scheduling mechanism, the company can provide a flexible and stable OTD lead time to its customers.

5.3 System Composition and Architecture

In analyzing the above case, we can conceive four different kinds of decision stations, which are presented in figure 2. The roles of these decision stations are described as follows:

Decision station DS_C is designed to support demand/capacity planners. Its decision model DM_C includes the following criteria:

$C_C = \{C_C^L, C_C^{CM}, C_C^{CP}\}$,

where $C_C^L = LT$, $C_C^{CM} = \{R_{sales}, C_{mk}\}$, $C_C^{CP} = C_{prd}$, LT stands for lead time, R_{sales} is sales revenue, C_{mk} is marketing cost, and C_{prd} is production cost. The action space $A^C = \{\overline{O}_{rate}, \overline{P}_{cap}\}$, where $\overline{O}_{rate}$ is the average demand and $\overline{P}_{cap}$ is the average production capacity per shift. These are actions by means of which the unit instructs other stations to achieve them as objectives. The sensor can fetch real-time information about the current size of orders in pool, compute average demand for recent period, for example last day or last hour, the current production capacity, and alert users when actual and/or production capacity is beyond the user-defined limits.

Decision station DS^M is designed to support marketing managers for short-term marketing control. It captures the real-time information of sales orders and provides marketing managers with trend analysis. Marketing managers can control demand by changing product price, product mix, advertising, as well as by following other promotional strategies.

Decision station DS_P is designed to production managers for short-term capacity control. It captures the real-time information of current production capacity and provides marketing managers with cost analysis. Production managers can control capacity by hiring temporary employees, adding shifts, and subcontracting.

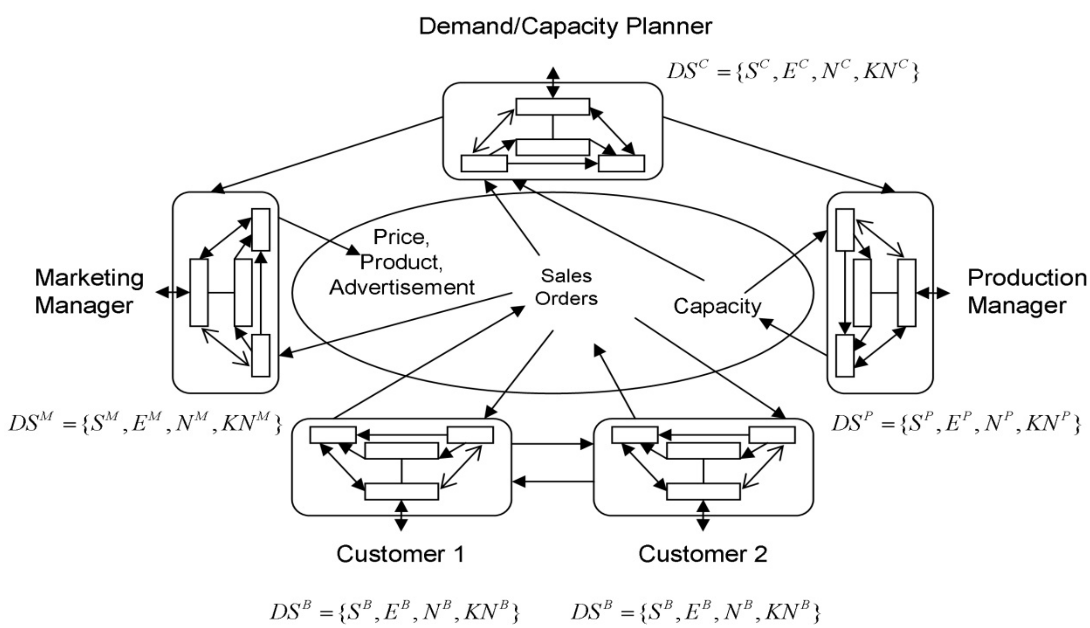

Figure 2. System architecture for lead time management.

Decision station DS^B is designed for buyers, i.e. customers on the Internet. When a customer places an order on the Internet, a default standard order-to-delivery lead time is placed in this order. However, if the customer is eager to get the product, he/she can negotiate with the other customers to advance the order. Decision criterion is customer's utility of due date of the order and the agreed compensation. The customers could use multiple criteria utility model to support his/her negotiation. Unlike the coordination among DS_C, DS_M, and DS_P, which is static, the relationship between any two DS_B s is dynamically established.

As a whole, this IDS can be expressed as:

$$IDS_{LT} = DS_C \cup DS_M \cup DS_P \bigcup_{i=0}^{n} DS_{B_i},$$

i.e. including one decision station for demand/capacity planner, one decision station for marketing manager, one decision station for production manager, and possibly decision stations for customers.

5.4 Prototype Implementation

In order to illustrate the framework and conduct simulation studies, we developed a prototype for the chosen problem using Java. A sample screenshot of the decision station for demand/capacity planner is shown in Figure 3. The left panel of the screen is demand and capacity monitor, i.e. the sensor S^C. The sensor can capture and calculate required data in real-time or in a period of delay (it is used to support our simulation study). The right panel is a queuing model to support lead time decisions, where two decision variables, the mean demand (shown as order arrival rate) and production capacity are input parameters.

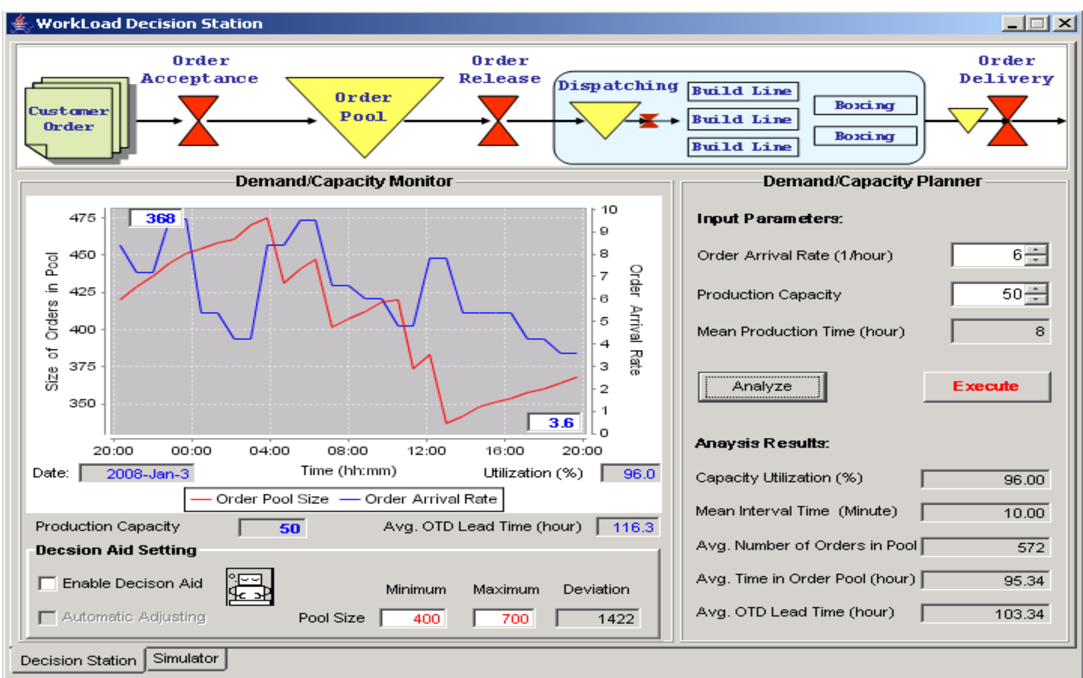

Figure 3. A prototype of decision station for demand/capacity planner

A planner can use queuing model to generate various alternatives, i.e. different combination of order arrival rate and production capacity. When the planner is satisfied with analysis result, he/she can pass control information to the decision stations for marketing managers and production managers, triggering other decision making processes.

6. Simulations

In order to evaluate the viability of the approach we have performed simulation experiments with the prototype. The two factors included in our study are information delay and information coordination. Information delay is a key independent variable since it allows distinguishing between the isolated "toolbox" model of DSS and Decision Station that emphasizes continuous monitoring and action. In the simulation experiment, it is manipulated by setting an interval between the time when relevant data are created and the time when the data are received and acted upon by the decision maker.

Three levels of information delay are set in this simulation:

Real-time: 50 minutes;

Delay 10: 500 minutes;

Delay 20: 1000 minutes.

Information coordination refers to information control and feedback by the aid of control information I^C and reference information I^R. In our experiment, we setup three types of information control:

Controlling marketing department by setting up an expected normal demand;

Controlling production department by setting up an expected normal production level;

Controlling both marketing and production departments.

When examining the effect of control information, we assume that production and marketing departments are able and willing to follow the instructions from demand/capacity planner.

Regarding information feedback, we designed an experiment in which either marketing or production department may be unable to fulfill the instruction from demand/capacity planner. If information feedback is enabled, they can send this information (e.g. the lack of capacity) to the planner, and then planner can adjust his/her instructions correspondingly. Simply stated, with information feedback, the demand/capacity planner will have a broader control scope. For example, without information feedback, the planner assumes that marketing department is able to adjust demand to any level between 5 orders per hour and 7 orders per hour. But in fact, the marketing department might only be able to achieve a demand level between 5 orders per hour and 6 order per hour. Due to the lack of feedback, the planner might lose a chance to do the other corrective actions, e.g. decreasing production capacity. In the experiment, we set up four types of information feedback:

Information feedback from both marketing and production;

Information feedback from marketing only;

Information feedback from production only;

No information feedback.

Cumulative deviation of actual output from predetermined target is used as a measure of performance. In the simulation, it is the summation of absolute deviation of actual order pool size from the predetermined boundaries:

$$\sum_{i=1}^{N}[Max(O_{size}^{i}, O_{low}) - Min(O_{size}^{i}, O_{high})]\Delta t ,$$

where O_{size}^{i} is actual size of order pool at the simulation time t_i , Δt is the time interval between two consecutive checks of the order pool size (in our cases, it is one second), and O_{low} and O_{high} are the predetermined boundaries of order pool.

Our expectations are formulated through the following hypotheses:

H1: The level of information delay is negatively related to decision performance.

H2: The level of information control is positively related to decision performance.

In our case, it refers to controlling both marketing and production department will achieve better performance than controlling either marketing or production department.

H3: The level of information feedback is positively related to decision performance.

In our case, it refers to receiving information feedback from both marketing and production department will lead to better performance than receiving information feedback from either marketing or production department, and receiving information feedback either from marketing or production will lead to better performance than receiving no information feedback.

In our scenario the arrivals of purchase order from website follows Poisson distribution with the mean of six orders per hour. The production time of finishing one batch of orders follows exponential distribution with the mean of eight hours.

In addition, we set up simple decision rules. If the current order pool size is bigger than the upper limit, the decision aid will either decrease the mean of order arrivals down to three orders per hours or increase production capacity up to 100 orders per shift. If the current order pool size is smaller than the lower limit, the decision aid will either increase the mean of order arrival up to nine orders per hours or decrease production capacity down to 50 orders per shift.

7. Results

We first consider the impacts of information delay and information control (i.e. sending controlling information by the demand/capacity planner). Results of ANOVA test revealed no significant interaction between information delay and information control (p = 0.656). The deviation of order pool size is significantly related to the level of information control ($p <$ 0.001), while information delay does not appear to have significant impact (p = 0.192).

Further, we do contrast tests to compare the means of the three levels of information control. Contrast 1 checks the difference between controlling marketing and controlling both marketing and production. Contrast 2 looks at the difference between controlling marketing and controlling production. Contrast 3 examines the difference between controlling both marketing and production and controlling production. The results are shown in table 2.

Table 2. Contrast tests: information control

Contrast	Value of contrast	Std. Error	t-value	Sign.
1	-7,388	8,473	-0.872	0.194
2	-77,282	14,748	-5.240	0.000
3	-69,894	14,631	-4.777	0.000

Thus, there was no significant difference between controlling marketing and controlling both marketing and production. However, controlling marketing only will achieve significantly ($p < 0.001$) less fluctuation in order pool than controlling production only. Similarly, controlling both marketing and production will get significantly ($p < 0.001$) less fluctuation in order pool than controlling production only. This provides partial support for hypothesis 2.

It is somewhat surprising that the impact of information delay was insignificant in the overall test. However, the interaction plot reveals some interesting insights (Figure 4). If we drop the case of controlling production only from consideration, it turns out that information delay is significantly related to the deviation of order pool size at $p= 0.001$. Thus in this case the Hypothesis 1 also finds some support. We will provide some justification for the effects of controlling production in the discussions.

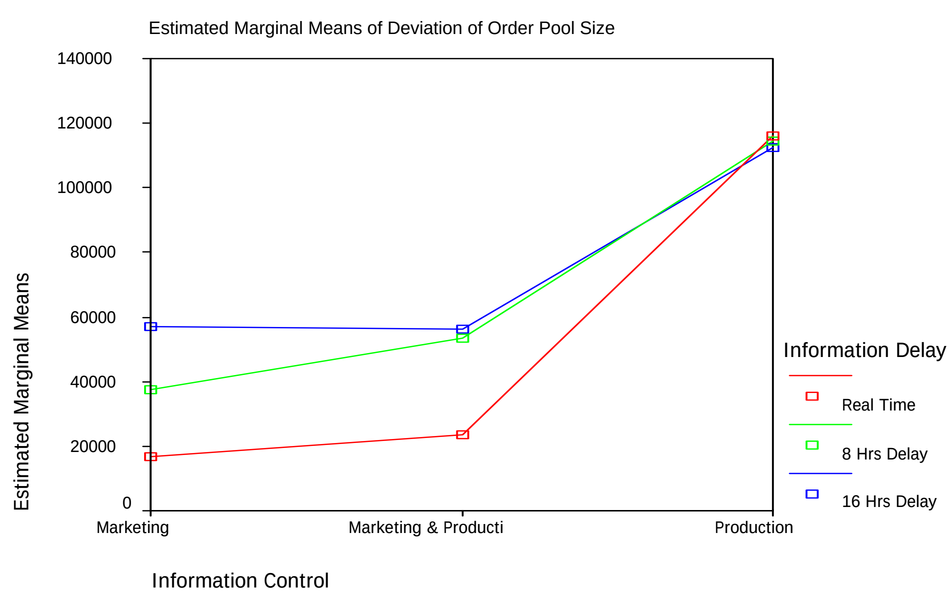

Figure 4. The interaction plot

To identify how the level of information feedback affects decision performance, we do three contrasts test. Contrast 1 compares full information feedback with no information feedback and contrast 2 compares information feedback from marketing with no information feedback, while contrast 3 compares information feedback from production with no information feedback. The results are shown in table 3. Both Contrasts 1 and 3 are significant at $p < 0.05$, but contrast 2 is insignificant. It means that receiving information feedback from marketing department only does not significantly improve decision performance significantly compared to no information feedback at all. On the contrary, receiving information feedback from production or from both marketing and production can significantly improve decision performance compared to no information feedback. This provides an overall support for hypothesis 3.

Table 3. Contrast tests: information feedback

Contrast	Value of contrast	Std. Error	t-value	Sign.
1	-39,063	22,290	-1.766	0.041
2	5.38	26,928	0.000	1.000
3	-43,580	22,063	-1.971	0.027

8. Conclusions

The paper has introduced the framework for distributed decision stations. The framework extends the notion of situated DSS to support distributed decision making. To illustrate the idea a prototype system for workload balancing has been implemented. Overall, the simulation experiments have provided support for our expectation that information recency and coordination improve decision quality.

Some apparently counter-intuitive results relate to coordination with the production department. The major reason is that production has limited flexibility in its capacity, i.e. production capacity cannot be changed immediately. In simulations, it usually takes eight hours to finish one batch before production capacity could be adjusted. For this reason, even though decisions can be made with timely information the actual implementation is slower.

Future work could be focused on developing a technical architecture to support the framework. For this reason, it is worth investigating potential applicability of advanced technologies, such as software agents, to build a solid and flexible structure supporting the conceptual framework.

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