UNCERTAIN DEMAND & SUPPLY NETWORKS MANAGEMENT: APPLICATION TO A REGIONAL HEALTH CARE SERVICE

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A Local Sanitary Agency – LSA operating in an Italian region can be described as a multi-stage multi-service-center chain, such that it can be modeled by a Collaborative DEmand and Supply NETwork (*CO-DESNET*[1]). Such network consists of an organization of service centers which operate in the same health care-dedicated line and interact together to facilitate the patients' flows along the chain of sanitary services. In order to assure effectiveness and efficiency to the health care network, two main problems have to be approached: 1st. how should the different phases of health care be organized in the service centers of the network such as to assure to each component center a sufficient capacity and cost coverage without congestion? 2nd. how could a collaborative service planning strategy be defined such as to assure to the health care network, as a whole system, clear perspectives of sustainable operations and development? This contribution will discuss an admissible solution of the LSA service planning problem, assuming that such system be modeled by a network of service center under demand uncertainty. The model here adopted will describe the network in terms of negotiation among the service centers (i.e., the "agents" of the network), and conditions supporting collaborations among the component agents will be derived.

Keywords: Health care systems; Multi-agent networks; Supply Chains; Demand uncertainty; Cooperation.

1. INTRODUCTION

Besides in the production and service enterprises, the management problems in complex networks of service centres also begin to be approached by using optimisation models of large-scale multi-agent supply chains (as the ones presented in the book by Tayur et al., 1999, Supply Chain Council, 2001; Bullinger et al., 2002). Main motivation for applying this approach is due to the similarity of the organizations of a network of production firms and of a network of service centres, even if dedicated to health care. In the former case, a collaborative negotiation between each pair of production forms occurs in order to have a balanced transfer of parts from a firm to the other, in such a way to assure to both of them a good income. In the latter, a collaborative interaction between each pair of service centres occurs in order to assure a reduced waiting time to patients asking for service, and a sufficient utilization of the centre service capacity, as well. The problem approached in this contribution is just to apply concepts and models developed in the frame of multi-stage production system management to a multi-centre regional health care organization: the goal is to derive suggestions for a good management of the patients' flows along the chain of service stages.

Owing to recent law modifications, in Italy a new heath care model is now based on the capacity of the service

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organization to create value instead of its old institutional goal of assuring service whenever. Such a new servicing approach forces the sanitary agencies to produce and supply services in quantity and quality which could correspond to the customer's requirements. Then, the necessary new organization must be calibrated on the persons' need that means to facilitate the service's accessibility and to connect into a common information network all centres which compose the whole regional health care agency. The present contribution has the scope of proposing a model of a *Local Sanitary Agency (LSA)* which features and operation mode could be used as an example for real implementation.

The paper contents are as follows.
Section 2 introduces a model of a regional health care organization (here referred to the Piemonte region in North West Italy) in terms of an uncertainty-affected DESNET. Section 3 will present a mathematical formulation of the health care network, based on that idea that each centre will negotiate with downstream centres for addressing them its own throughput of patients. Section 4 will analyze some conditions for solving the problem of optimising interactions among the service centres, such as to define some criteria for planning collaborative local service strategies. The effects of the local service capacities as well as of the demand variations in time will be discussed, such as to propose some network innovation suggestions.

2. INTRODUCING A MODEL FOR A REGIONAL HEALTH CARE NETWORK

Assuming that the central node of a local health care system (usually denoted as *Local Sanitary Agency - LSA*) is the hospital, the main goal of a mid-term management of the offered sanitary services is to control volumes of patients flowing from a centre to another in such a way to avoid congestion and reduce queues as much as possible: this is indeed the main goal of the LSA management. To this aim, all types of service centres which compose the health care system has to be described and included into a network, as in Fig. 1.
As above outlined, the hospital is the main centre, which collects flows of patients coming from several upstream centres, namely: day-hospital centres, local surgeries and consulting rooms, here considered as intermediate stage centres; medical officers and specialists, i.e. the upstream stages or input stage for patients. In order to avoid congestion in these critical health care services, the patients' demands have to be filtered by upstream centres, through careful diagnostics and prevention actions. Besides these, the upstream centres have to address their patients to downstream ones, according to the service capacity values of these latter.
It follows that an effective/efficient management of the flows of patients in the LSA network requires availability of a formal model of the organization of the service network, as well as a model of the exogenous demand for health care servicing arising from the local region under the responsibility of the LSA. The former model should be able to include the most important parameters of the LSA organization, namely the service capacity at each centre, the service quality level, the related costs, and mainly the interactions among different service centres.

In the present approach, Fig. 1 outlines the types of centres considered as component parts of the LSA organization: each centre type corresponds to a number of real centres of the same type, operating "in parallel" within the LSA local region. Thus, the real service network appears to be a multi-stage multi-centre flow-line-type system (of the same type as a multi-stage multi-agent supply chain, such as described in Villa, 2001; Villa, 2002; and Zhen & Possel-Dolken, 2002), where patients will enter at the input stage centres and will either go out from any centre, or flow to a downstream centre.
The objective of such a model will be to find a pattern of patients' flows over the service networks such to optimise the utilization of the service capacity at each centre and minimize queues. The following Section will introduce a formal model of the service chain just stated in the form of minimization problem of service costs and patients queues, under finite service capacity constraints.

3. A CO-DESNET MODEL OF A REGIONAL HEALT CARE SYSTEM

The CO-DESNET model of a regional health care system is based on the idea that such system consist of an "open service network" within which the component service centres interact together by addressing patients from a service stage to another, such to reduce the patients' queue time and to maximize the service capacity utilization (and then, the income from the supplied services, as required by the LSA management).
Then, each centre wants either to address as soon as possible the served patients to the downstream centres, or to release as soon as possible patients without residual health problems. On the other hand, each downstream centre (able to apply more sophisticated sanitary services) wants to receive a number of patients coherent with its own capacity, but not so many to increase queues (and then degrade its service level).

The flows of patients from a centre to another occurs within a co-ordinated protected system, the LSA which goal is to manage the global health care service in such a way that local centres co-operate through collaboration agreements. The collaboration between a centre at a stage and a downstream centre consists of the exchange of information about the patients' queues at the two centres: as a consequence, the addressing of patients from the upstream centre to the downstream one depends on the downstream queues' lengths. To this aim, the LSA controls the flows of patients in terms of numbers and costs of supplied services. Its own important regulation variables are the unitary costs of services offered by centres and a potential support in improving the service capacity of the centre.

For sake of simplicity (but without any loss in generality), let us consider a health care system modelled by a *CO-DESNET* composed by 4 service centres, belonging to 2 different stages. Two internal places for patient flows addressing, one internal and the other between the exogenous social environment and the input service stage, define the interactions among the agents together and between agents and the external world.

At the input stage, two services (denoted by index *n=1,2*) release served patients towards the two centres belonging to the following stage (denoted by index *n=3,4*). These ones will apply final servicing operations. Each "agent" *n* (i.e. the management of a component centre) is modelled by a service optimisation problem which variables to be optimised are the patients' volumes. This model describes the centre minimization of its own costs under the constraints describing the patients' queue dynamics and the service capacity saturation.

The notations adopted for the service centres *n=1,4* are the following (all referred to time period *t*):

$X_{n,t}$	volume of patients arrived at centre *n*;
$Y_{n,t}$	volume of patients served by centre *n*;
$I_{n,t}$	queue of patients at centre *n*;
c_n	queuing cost for individual patient;
r_n	servicing unitary cost;
C_n	service capacity of centre *n*;
A_t	total input of patients au time *t*.

The resulting model for the centres *n=1,4* is as follows:

$$\min_{X,P,Y} J_n = \sum_t (c_n I_{n,t} + r_n Y_{n,t}) \tag{1}$$

$$I_{n,t} = I_{n,t-1} - Y_{n,t} + X_{n,t}; \quad I_{n,t=0} = I_n^0 \tag{2}$$

$$Y_{n,t} \leq C_{n,t} \tag{3}$$

$$X_{n,t}, I_{n,t,F}, Y_{n,t} \geq 0 \tag{4}$$

The four centres are assumed to belong to the same *CO-DESNET* modelling the considered LSA. That means that some conditions have to regulate interactions among partner centres, namely:

I. Conditions stating that the volumes of patients either outgoing from upstream centres or arriving from outside, have to be accepted by the downstream ones:

I-a. All parts served by an upstream centre will be received by the downstream ones, depending on their addressing there:

$$Y_{n,t} = \sum_{m=3,4} X_{n,m,t} \tag{5}$$

I-b. Each downstream centre will accept patients from any upstream centre

$$X_{n,t} = \sum_{m=1,2} X_{m,n,t} \tag{6}$$

I-c. The global demand for health care coming from outside have to be served:

$$\sum_{n=1,2} X_{n,t} - A_t = 0 \tag{7}$$

where the demand uncertainty is modelled in terms of uncertain perturbations with a basic component occurring within a given frequency band and a stochastic normally distributed component, such that

$$A_t = A_t + dA_t; \text{ being } dA_t = N[0, \sigma_A]; \forall t$$

II. Condition stating that the service volumes of the centres belonging to a same stage have to be balanced according to the respective efficiency:

$$\frac{1}{C_1}(Y_{1,t})^2 - \frac{1}{C_2}(Y_{2,t})^2 = 0 \tag{8}$$

$$\frac{1}{C_3}(Y_{3,t})^2 - \frac{1}{C_4}(Y_{4,t})^2 = 0 \tag{9}$$

Note that these last two conditions state the effective collaborative rules for the service centres belonging to a common *CO-DESNET*. In practice, the agreement to be a network partner states that each service centre agrees in supplying services, for the patients' demand needs, by using its own capacity at a rate which must be balanced with the capacities of the other partners: no centre will receive a demand for servicing "unbalanced" with respect to the others.

The global management problem results from the whole set of conditions (1) to (9) above stated. It consists of a large-scale non-linear stochastic optimization problem, for which existence of an optimal solution can be proven according to existing results as in (Sethi & Zhang, 1994; Brandimarte & Villa, 1995). By applying Lagrangian relaxation, the complete optimisation problem can be split into four optimization sub-problems, all interrelated together, each one linked to a component centre *n*, namely:

- for the centre *n=1* (the same for *n=2*)

$$\begin{aligned}\max_{\alpha,\beta,\gamma,\delta,\eta} \min_{X,P,Y} \Pi_1 = \sum_t [c_1 I_{1,t} + r_1 Y_{1,t} + \\ + \alpha_{1,t} Y_{1,t} + \beta_t X_{1,t} + X_{1,3,t}(\gamma_{3,t} - \alpha_{1,t}) + \\ + X_{1,4,t}(\gamma_{4,1} - \alpha_{1,t}) + \delta_t \frac{1}{C_1}(Y_{1,t})^2]\end{aligned} \tag{10}$$

- for the centre *n=3* (the same for *n=4*)

$$\begin{aligned}\max_{\gamma,\eta} \min_{X,P,Y} \Pi_3 = \sum_t [c_3 I_{3,t} + r_3 Y_{3,t} + \\ + X_{3,t}\gamma_{3,t} + \eta_t \frac{1}{C_3}(Y_{3,t})^2]\end{aligned} \tag{11}$$

The variables written by Greek letters denote the Lagrangian variables, by which the constraints have been included into the augmented global functional to be minimized.
All above stated functional terms have to be maximized with respect to the Lagrangian variables: *this maximization will allow to obtain the co-ordination conditions.*

4. CONDITIONS TO ASSURING COOPE-RATION IN THE MULTI-CENTER NETWORK

Some conditions which can assure collaborative operations of all centres belonging to the *Health Care CO-DESNET* can be obtained by analysing the Lagrangian variables, introduced in the relaxed formulation. The motivation of this analysis approach is that such Lagrangian variables denote co-ordination costs.
But, before to analyze such conditions, some considerations have to be developed concerning the uncertainty affecting both the patients' volumes and the service capacity values at the network centres.

4.1. Time Scale Separation for Uncertainty Management

As above stated, we shall consider a health care system facing possibly uncertain demand from its social environment: it means that the demand for sanitary services presents a time-dependent evolution with a mid-term component, which can usually be estimated, and a very-short-term random component.

This type of evolution of the exogenous input variable has inspired the "singular perturbation" approach (See Kokotovich, 1984 and the following wide literature): in principle, it is based on the idea that events tend to occur in a discrete spectrum, to which a *hierarchy* of frequency-separated controls can be independently applied. Then, in modelling the decisions to either control or counteract events at each frequency of occurrence, events occurring at a lower frequency can be managed with slowly acting decisions, by assuming that faster and faster events (as the random ones) could be filtered out. On the other hand, events occurring at a higher frequency can be managed with the assumption that quantities that vary slowly could be treated as constant.

Owing to this idea, the two types of uncertainty affecting a health care system, either on the service demand or on the centre service capacity, evidently belong to two separated frequency of evolution: the latter will change at a slow rate, whilst the former presents a higher-rate of evolution.

Then, the mid-term management of the Health Care CO-DESNET, as for the re-organization of the service offered by the network centres, requires to approach the above stated optimisation problem, under the assumption that the centre capacity parameters are constant while the random uncertainty on the exogenous service demands could be filtered out. The aim, indeed, is to obtain a good dimensioning of the local service strategies in such a way to be able to estimate if and when their respective capacities should be improved.

4.2. The Mid-Term Management of the Health Care CO-DESNET

Some conditions which characterize an optimal service strategy can be drawn by analysing the Hamiltonian function components (10) and (11) of the above stated optimisation problem. Here each Lagrangin variable plays the role of co-ordination cost, thus evidencing actions/decisions which the managers have to adopt in order to become more collaborative.

Let us first refer to variable $\alpha_{n,t}, n=1{,}2$, namely to the two co-ordination cost concerning the volume of patients served by each upstream centre and addressed to both downstream centres. In case this volume increases, the acceptance of patients at downstream centres could be restrained, as shown by the counteracting cost $\gamma_{n,t}, n=3{,}4$, which value is conditioned by the value of the downstream centres performance index. Thus, a balance between upstream and downstream stages utilization is induced ("vertical co-ordination").

The Lagrangian variable $\delta_{n,t}, n=1{,}2,$ denotes the co-ordination cost concerning volumes of served patients to be shared between the two first-stage centres ("horizontal co-ordination"), related to condition (8). The squared valued functions force a split of the volumes of patients to be served respectively depending on the rate between the two centres' throughputs $Y_{n,t}, n=1{,}2,$ and the respective centre capacity utilization, estimated by $\frac{1}{U_{n,t}} = \frac{Y_{n,t}}{C_n}$, for *n=1,2*. The cost δ_t forces to minimize unbalances between concurrent centres.

The companion Lagragian variable $\eta_{n,t}, n=1{,}2,$ operates in a similar way as δ_t, on the two firms belonging to the second stage, as in constraint (9).

5. SOME CONCLUDING REMARKS

The above sketched analysis of the effects of Lagrangian variables in solving the network management optimization problem allows to derive some comments and suggestions for the management and re-organization of a regional health care network, according to reasoning approach as in case of multi-agent networks (see Rossetto and Villa, 2003).

First, the stability of the *CO-DESNET* operations can be assured, since:

a. each endogenous perturbation (e.g. due to a variation of some internal variables, as produced volumes) is counteracted by the Lagrangian variables (thus justifying their denomination as "co-ordination costs"), which force the set of interactions to come back to equilibrium;

b. each exogenous perturbation (i.e., on the number of incoming patients) generates new additional costs to the whole set of component enterprises, thus forcing internal balancing effects.

As examples of these preliminary considerations, the reactions against perturbation of an internal service rate are outlined.

Assume that the production volume $Y_{1,t}$ increases at a certain time *t*. As a consequence, the "vertical co-ordination" cost variable $\alpha_{1,t}$ also increases, thus forcing an increase of the volumes to be purchased by second-stage centre ($X_{n,t}, t = 3,4$). But the other effect of the same co-ordination cost variable $\alpha_{1,t}$ is to force a reduction of the first-stage production rates ($Y_{n,t}, t = 1,2$), as in (5). In addition, the Lagrangian variable δ_t denoting the co-ordination cost for the volumes of production to be shared between the two first-stage centres, also increases; this last evolution should counteract the dynamics driven by α_t.

In practice, any variation of the served patients' throughput of a component centre should be paid by the same centre proportionally to its own service efficiency.

Second, the effectiveness of a *CO-DESNET*, in terms of average costs of patients which use the considered health care system (i.e. queuing costs), as well as costs of the service supply, both to be controlled by the LSA management.

Two main goals drive the decisions of a LSA manager: on one hand, to assure that each service be easily accessible by potential customers, that are persons living in the neighborhood of the center and calling for its sanitary service; on the other, to assure that each patient, arrived at a service center, could wait for a limited time before being served, such to guarantee a high service efficiency and to keep lower and lower the number of patients both going around from a center to another (thus, uncontrollable) and going out of their LSA network towards other sanitary systems.

Both above sketched goals are clearly verified by the network model above stated, since the CO-DESNET modeled by (1) to (9) should impose to each component center agreement conditions which will assure co-operation, and such model suggests to assure the exogenous demand satisfaction with the best possible internal equilibrium of volumes, which are assigned to partners according to their respective capacities.

More precisely, balancing the utilization of service centers belonging to the same stage allows to assure the minimum queue lengths (and then, minimum waiting time) at that stage. This balance of service demands has to be obtained through an optimal pattern of patients' flows addressed to the parallel centers; in practice, this can be really obtained by two complementary actions: by informing potential customers about the center status and by suggesting them the more convenient center to be used. Depending on these actions, both the service demand and supply can be controlled, and the service efficiency can be compared with a selected benchmark.

The co-operation conditions suggested by the model (see (8) and (9)) and the resulting optimized service strategy (in the average conditions) give suggestions for organizing an "Information & Communication System (ICS)" connecting all service centers, such that each one could have a complete view of the network status (this is a theoretical conditions which contributes to guarantee the global optimality of the set of collaborative service strategies, as in Villa & Cassarino 2004).

The suggested ICS will be the effective control tool for the LSA manager. Proposal of an ICS organization, even if partial and dedicated to some critical and important sanitary services is going to be defined just on the line here presented, also with the purpose of considering spatial factors of analysis and horizontal interaction among 'competitor' centres, i.e. offering the same type of services.

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Figure 1. Conceptual scheme of the Local Sanitary Agency organization in terms of a multi-stage multi-centre-type network.