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Holonic systems for decision-making in hospital mergers

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Abstract Health crises, such as epidemics, require a precise decision-making and control process between the different components of the health system in order to manage patients well. In this context of improvement, governments in various countries create GHTs, *i.e.*, hospital mergers or, in French, “*Groupement Hospitalier de Territoire*”. The purpose of this article is to discuss three more or less (de-)centralised decision-making scenarios within a GHT. These different decision-making models will be applied to a specific GHT from the Loire region in France. We propose these scenarios by implementing the concept of agent in the decision-making system of this GHT, because the introduction of this concept through holonic systems is a way to efficiently integrate data into systems while taking account of various constraints. Before proposing these scenarios, this article first reviews the literature on GHTs from 1980 to 2021. This review shows that decentralized decision-making seems to be a key factor in the success of a GHT.

Keywords : GHT (hospital merger) ; Holonic system ; Crisis ; (De-)centralised decision making; Hybrid control.

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1 Introduction

The poor decision-making to control and coordinate activities in GHTs (hospital mergers or, in French, “*Groupements Hospitaliers de Territoire*”) presents a weakness in the management of health resources. This management relies on decisions made on the three levels shown in Figure 1. The first one is the strategic level on which the GHT makes long-term decisions (over one year or longer) such as the choice of its information system. Conversely to such long-term decisions, the other two levels involve decisions on a shorter horizon of time. This article deals with the third level which concerns the operational control (shortest term, *i.e.*, a few days) of a GHT with decisions such as allocating patients to resources (care givers, rooms, equipment, etc.) depending on capacities, changes of these capacities, deprogramming of surgeries, transportation of patients from a saturated hospital to another, etc. Epidemics and health crises, such as COVID-19 appeared in Wuhan, China in 2019, demonstrate the importance of the organization of decision-making in GHTs due to the rapid spread of the virus, lack of appropriate local information and poor coordination among the health actors [33]. This organization is important as it may greatly influence the load balance between hospitals. Indeed, given the NP-completeness of some decisions, centralized decision-making is generally not the best approach because the optimal decision would take too much time to compute. Hence, the best organization of decision-making will often be a trade-off between decentralization to obtain reactivity and centralization to aim at optimality. In this context, this article synthesizes the literature on the main causes of the success and failure of GHT experiments in the world, and proposes three decision-making scenarios in the GHT “Loire” (region in France) in the event of a health crisis. These scenarios allow understanding when and how to (de-)centralize decision-making in this GHT. More technically, we study the distribution of constraints among the different hierarchical levels in this GHT. This study of the decision level on which every constraint should be taken into account seems to be an original scientific contribution. In other words, our goal is to make rough allocation decisions (*i.e.*, with few constraints) on the highest hierarchical level, and detailed decisions (*i.e.*, with all constraints) on the lowest



Fig. 1 Levels of decision-making

hierarchical level. This paper is organized as follows. Section 2 reviews the literature supporting decentralized decision-making in GHTs. Section 3 proposes our three scenarios of decision-making in a GHT. Section 4 discusses the main findings of this review and highlights opportunities for future research. Section 5 concludes.

2 Literature supporting decentralized decision-making in a GHT

2.1 Materials and methods

As aforementioned, we first review the literature on GHTs around the world in order to know whether (de-)centralized decision-making may be relevant for a GHT. We use the Google Scholar and Web of Science databases to find such scientific articles. This is because these databases have the highest number of citations [2, 19]. The literature review presented here is based on the following plan: (i) identification of research problems (presented below); (ii) collection and selection of articles (combinations of keywords (different synonyms of GHT, decision-making and holonic systems), and (iii) presentation of research results and determination of the shortlisted articles (Application of 5 selection criteria to filter adequate articles.) (these parts are further detailed in the supplementary material¹). In order to understand and identify the nature of the decisions and the structure of the holonic system supporting these decisions in a GHT in the context of a crisis, we define our research question as follows: *How do GHTs manage their decision system in the case of epidemics?* To answer this question, three specific Research Problems are formulated as follows:

- *RP1*: Based on GHT experiences around the world, what are the causes of a failed merger?
- *RP2*: How do GHTs manage their decision system in normal situation?
- *RP3*: What are the possible models to integrate in order to better manage the decisions in a GHT, especially during health crises?

2.2 Results

2.2.1 Definition of the concept of GHT

GHTs are created by merging and combining different categories of hospitals (public/private, specialist/generalist, etc.) to establish a network of specialized and/or

¹ Supplementary material presents the different combinations of keywords searched in the literature review, exclusion criteria, a figure presenting the percentages of countries in which the GHT concept is mentioned in the articles found, and articles not referenced in this article: https://github.com/disp-lab/centr_vs_decentr/blob/master/SOHOMA2023.pdf

non-specialized hospitals. Such a merger takes place either by the dissolution of one or more hospitals and their absorption by another, or by the creation of a new hospital from the dissolution of all the participating hospitals. Several countries around the world apply this concept in order to improve their health system. Some of such merges are successful, while others fail. Subsection 2.2.2 now summarizes the reasons of such successes and failures.

2.2.2 Successful and failed GHTs

The various qualitative and experimental studies of GHTs based on the articles in Table 1 and other articles cited in the supplementary material¹ show that GHTs provide a full range of health services to different populations and improve the access to specialized care, reduce wait and travel times, reduce costs due to improved quality of care, autonomy, and respect of their staff. The GHT present the merger of different types of hospitals (public, private, specialist and non-specialist), and it does not influence the success or the failure of the merger according to the articles. But the GHT may also fail due to many factors such as centralization of powers and the predominance of the support (main) hospital over the others. Moreover, some mergers do not seem to reduce costs because these merged hospitals become too large and reduce the well-being of patients.

Locations	Failure or Success	Staff respect	Cause of failure or success				
			Quality		Decision		
			Good	Poor	Autonomy	Centralization	Predominance
Ontario, Canada [9]	S		✓				
Malaysia [28]	S	✓	✓				
China (Hong Kong) [12, 32]	S		✓				
United Kingdom [8, 17, 26]	S	✓	✓		✓		
Denmark [31]	S	✓	✓				
Sweden [1]	S	✓			✓		
Norway [18]	F					✓	✓
United States : Mount Sinai and New York [13, 14]	F					✓	✓
United States, Canada, England, Finland, Israel, Norway and Sweden [22]	F					✓	✓
United States [24]	F			✓			✓
Queensland, Australia [25]	F					✓	

Table 1 Examples of GHT experiences

From the experience of successful GHTs in Table 1, success seems to occur more often when decision-making is decentralized. The centralization of the decision and the predominance of the Support Hospital (SH) seems to be the responsible for the majority of failed mergers. However, the more autonomy there is within a GHT, the

more successful this seems to be. This supports our work of using a holonic system to control GHT “Loire”, as now detailed in Section 3.

3 Three scenarios of organisation of (de-)centralized decision-making in GHT “Loire”

3.1 Overview of the operation of GHT

In order to understand the technical concept of GHT, Figure 2 shows an explanatory diagram of GHTs and Figure 3 the area covered by GHT “Loire” in France. Figure 2 shows that a GHT is composed of (i) a support hospital (SH), namely “CHU (Centre Hospitalier Universitaire) de Saint Etienne” in the case of GHT “Loire” shown in red in Figure 3, which manages (ii) mediator hospitals (MH) in yellow in Figure 3, *e.g.*, “CH (Centre Hospitalier) de Roanne”, and (iii) local hospitals (LH) in blue, such as “CH des Monts-du-Lyonnais”. Various data need to be considered in the organization of decision-making in this GHT. There are two types of data: (i) exogenous data such as the displacement of the epidemic and (ii) endogenous data such as the number of beds, the territorial dimension, hospital specialities and hospital staff. All these data must be taken into account to achieve the objectives of the GHT to provide a comprehensive and progressive range of care in its territory, organized around the clearly identified care pathway. Several studies [11, 20, 23, 29, 35] discuss the decision-making and steering in a GHT but they are generally oriented towards supplier problems and budgets. These five articles all conclude that the integration of the decision-making of all the institutions whatever their hi-

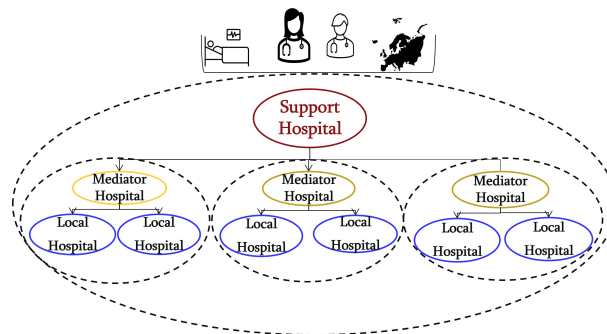


Fig. 2 Overview of a GHT

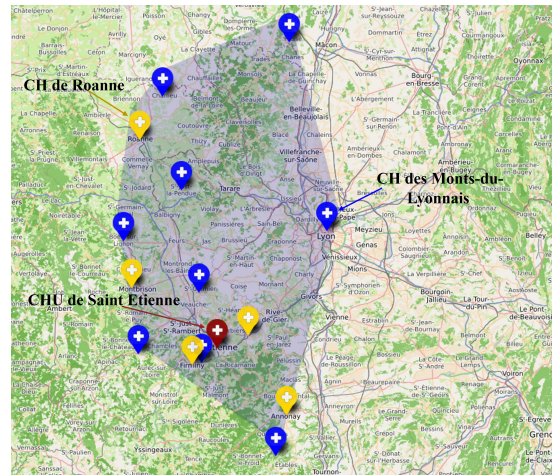


Fig. 3 GHT “Loire” in France

erarchical position is important. In Section 2, we noted that the main two causes of failed mergers seem to be the centralization of powers by SH and its predominance in decision-making. In crisis, such as COVID-19, several articles [3, 4, 15] (see also Footnote 1) show that the situations change, which requires the modification of the decision-making processes in order to adapt the control of patients’ pathway.

3.2 Holistic organization scenarios for GHT “Loire”

The use of holonic systems to manage and coordinate resources has been successfully applied to a variety of areas. In the hospital field, authors [7, 16, 21, 27, 30] (see more in Footnote 1) describe applications such as decision support systems in the organization of the extraction and implantation of organs, management of the care process, measurement and model of the dynamics of electronic medical record dissemination in hospitals, etc. Holonic systems are used in medical diagnostic system in order to implement a highly effective and robust disease diagnostic system on the Internet. In the context of crises such as COVID-19, other authors [5, 6, 34] (see more in Footnote 1) show that holonic systems are applied to model the spatial distribution of the virus. They also point out that the COVID-19 experience has shown that GHTs did not coordinate sufficiently during this pandemics, thus failed to ensure the appropriate treatment of patients. The problem is not simply a matter of deprogramming all the interventions of health facilities in the territory to compensate for a lack of resources, but also to steer and coordinate resources as precisely as possible in the complex, dynamic and highly uncertain context of such a crisis. The establishment of a holonic system in the context of a GHT allows proposing a prototype of the system of assistance to its steering for improving its management.

This subsection proposes our 3 scenarios with decision (de-)centralized to a more or lesser degree, than translates them into an objective function and constraints. We try as much as possible to keep the same decision variables for all scenarios in order to compare the efficiency of the (de-)centralization of decision-making. We define the following variables: H is the number of hospitals in GHT “Loire”, P the number of its patients, b_h the number of available beds in Hospital h , s_h the number of staff (doctors and nurses) available in Hospital h , t_{hp} the travel time for Patient p to Hospital h , T_{max} the maximum transportation allowed, n_h the number of patients in Hospital h . We use the following binary variable:

$$x_{hp} = \begin{cases} 1 & \text{if Patient } p \text{ is allocated to Hospital } h, \\ 0 & \text{otherwise.} \end{cases}$$

The allocation problem to be solved by the entire GHT may be described as the following MILP (Mixed Integer Linear Program):

$$\text{maximize } \sum_{p=1}^P \sum_{h=1}^H b_h x_{hp} \quad (1)$$

$$\sum_{h=1}^H x_{hp} = 1 \quad 1 \leq p \leq P \quad (2)$$

$$n_h + \sum_{p=1}^P x_{hp} \leq s_h \quad 1 \leq h \leq H \quad (3)$$

$$x_{hp} = 0 \quad T_{max} \leq t_{hp}, 1 \leq h \leq H, 1 \leq p \leq P \quad (4)$$

(Eq. 1) The objective is to allocate patients to hospitals with the largest number of free beds. (Eq. 2) Each patient must be allocated to a single hospital. (Eq. 3) The number of patients assigned to a hospital must be less than the number of staff in this hospital. (Eq. 4) The travel time between the hospital and the patient must not exceed a maximum time.

The rest of this subsection describes our 3 scenarios proposed to solve this MILP. Some of the constraints in this MILP are not taken into account by SH or MH in order to generate a “rough” allocation of all the patients in the GHT. Next, this rough allocation is detailed by MH or LH only with its patients but with all the constraints. We now describe our 3 scenarios:

- *Centralized scenario*: Figure 4 shows that SH makes its decision considering all the constraints of itself, MH and LH (number of beds and staff available). That is, SH allocates patients for the other hospitals in order to minimize the number of beds available given the lack of information on beds and staff available in other hospitals. This decision is sent to the MHs, which then distribute it to the LHs belonging to the same group. Hence, SH solves the problem of assigning all patients to all hospitals in the GHT. This allows SH to make decisions more optimal overall from the point of view of allocation in relation to distances, but less effective from the point of view of visibility of the free beds. In addition, the calculation time may be very long because of both size and computational complexity of the problem.
- *Decentralized scenario*: Figure 5 presents how the decision may be shared between all hospitals regardless of their hierarchical position. To keep the structure of the GHT administrative entity, SH makes the first and the last decisions taking account of the constraints of the crisis situation as SH knows of its number

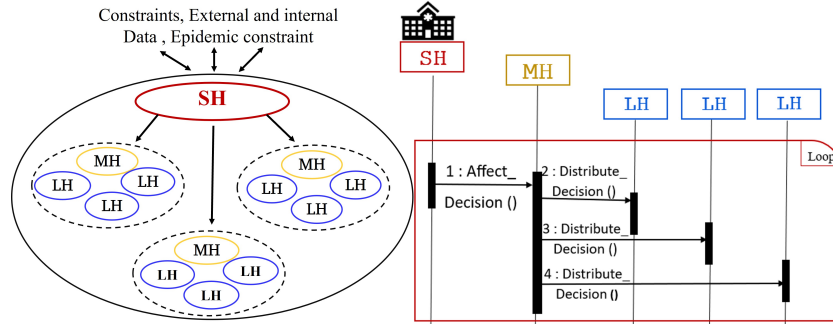


Fig. 4 Centralized scenario of holonic system for the GHT (SH is the Support Hospital, MH are Mediator Hospitals and LH Local Hospitals)

of beds and staff available. Then, SH allocates this decision to the MHs who distribute it to their LHs. Each hospital at any hierarchical level calculates its objective function taking into account its constraints (number of their beds available). From a technical point of view, all hospitals are considered as agents and constraints are calculated in the agents' local MILP, which is derived from Eq. 1. After each MH and LH has made its decision, it shares this decision with SH which carries out the final allocation taking into account all the constraints of all hospitals and the constraints in 4 in order to minimize the transportation time of all patients. The advantage of doing the calculation in agents' MILP is the fact

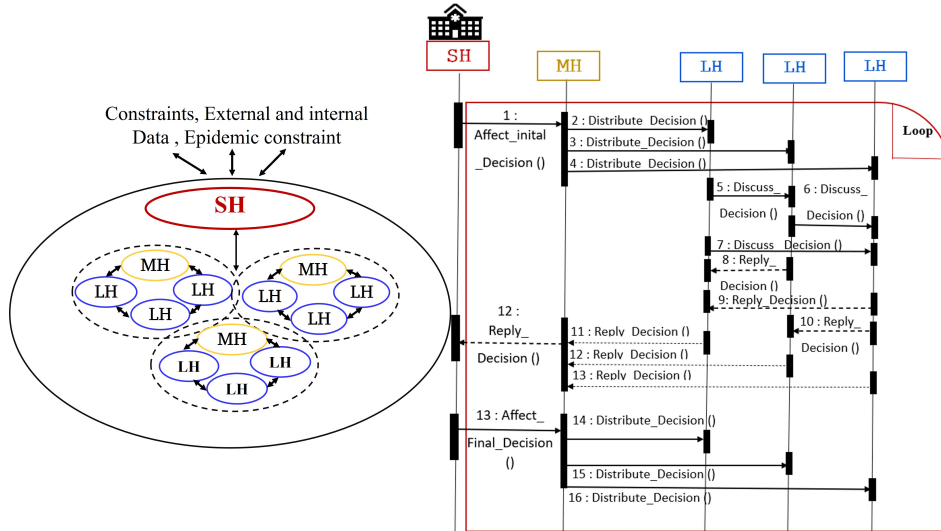


Fig. 5 Decentralized scenario of holonic system for the GHT (SH is the Support Hospital, MH are Mediator Hospitals and LH Local Hospitals)

that such a splitting of the problem into smaller problems reduces the calculation time of each agent while parallelizing these calculations on these different agents. The disadvantage is that the solution found by the interactions between (i) LH and MH only, and (ii) LH/MH and SH may be less effective overall.

- Hybrid decision scenario:* Figure 6 shows that SH makes the first decision to allocate patients minimizing the number of its beds available. This allocation takes into account the constraints of the crises and the constraints SH knows of (*i.e.*, number of free beds in SH). This decision will then be sent to all MHs which calculate for their LHs, then sent to SH to manage it and make the final decision taking account of the constraints in Eq. 4. From a technical point of view, therefore, the constraints of MHs and LHs will be taken into account in the MILP of MH. This will reduce the calculation time compared to pure centralization and will give a more efficient solution compared to pure decentralization.

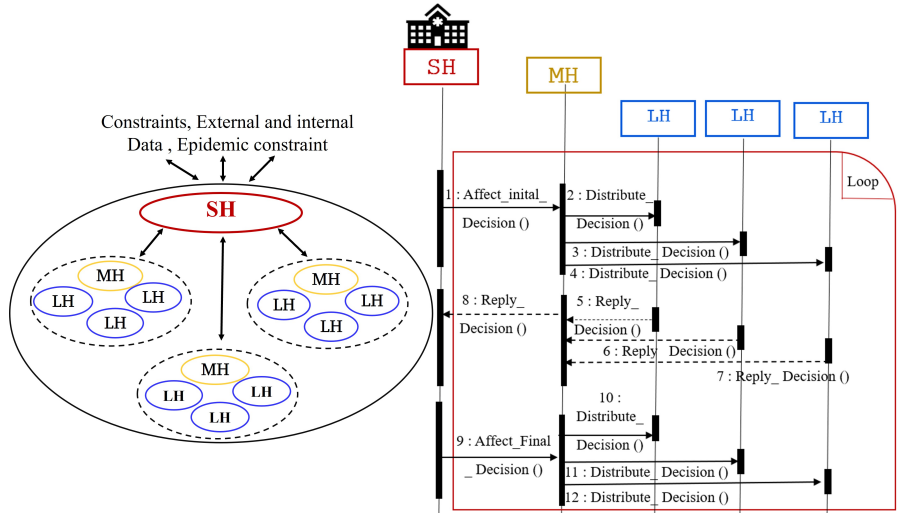


Fig. 6 Mixed holonic systems for the GHT (SH is the Support Hospital, MH are Mediator Hospitals and LH Local Hospitals)

The higher-level SH in these 3 scenarios creates a large framework of decision meshed centrally, then the autonomous agents take their decisions locally by interacting with each other in a decentralized way. It is then necessary to optimize the level on which every constraint is taken into account in order to make a trade-off between the following situations:

- MHs and LHs cannot make decisions until SH has made its decision:* Given the hierarchical structure of the GHT, SH makes the first decision by calculating its needs and taking into account the constraints limited by its poor knowledge of the other hospitals.

- *SH makes a lower quality decision and/or makes agents wait longer if SH considers more constraints:* If SH makes a decision by calculating the needs and problems usually with less constraints, it solves the less detailed MILP of the entire GHT quicker. Since this solution does not take all constraints into account, MHs and LHs next take the missing constraints into account in their local MILP, but only solved with the patients allocated to these MHs and LHs. The more constraints are taken into account by SH, the more it may take time to optimize, or not (because constraints may help the MILP solver). On the other hand, SH needs to solve a problem with many more patients than MHs and LHs, and SH may thus need more computation time.
- *Agents can more easily address limited environmental disputes and their uncertainties:* Each MH and/or LH can locally optimize its decision in a decentralized way easier and more efficiently. This result in a decision which is both feasible but not optimal for the entire GHT.

4 Discussion

The following discussion takes place in two phases. The first phase addresses the 3 questions RP1, RP2 and RP3 asked in Section 2, which allow us to understand the progress made in GHT. The second phase identifies opportunities and challenges.

We may summarise our answers to the above 3 Research Problems with the following answers found in the literature:

- *RP1:* Based on the experience in various countries, we may conclude that the centralization and predominance of SH in a GHT are the two main causes of failure.
- *RP2:* According to the general structural architecture of GHTs, decisions are usually made by SH and rarely by the committee of hospital representatives and these decisions must consider several constraints such as the number of beds, the territorial dimension... Such a structure of decision-making poorly manages GHTs during health crises, especially, COVID-19.
- *RP3:* Some GHTs have installed holonic systems in several areas, but they are not used to manage decision systems yet. COVID-19 has shown the weaknesses of the process of decision-making in GHTs.

Opportunities and challenges: Despite significant progress provided by GHTs, many research opportunities may be identified. The modeling of the 3 scenarios in Section 3 using holonic systems is among these opportunities. Modeling these 3 scenarios in the same simulation model will allow comparing them and determine which one generates the *best trade-off between reactivity (computation time) and optimality (quality of the allocation)*.

The scientific objective here is to optimize the division of the steering problem between techniques from Operational Research and holonic systems. To do so, the SH, MHs and LHs will all use the Operational Research solver “CPLEX” to opti-

mize their decisions, then interactions (between lower-level hospitals and their direct superior) will coordinate these decisions. As said above, some constraints may be modeled in either SH or MHs or LHs. The associated scientific question is to *identify the best level for each constraint in the 3 scenarios in Section 3.*

5 Conclusion

The (de-)centralization of decision-making by the support hospital (SH) with/without the mediator hospitals (MH) and local hospitals (LH) in a GHT influences its coordination and management, especially during health crises such as epidemics. This article studies the decision process in one GHT and proposes three possible scenarios in relation to its organization by integrating holonic systems.

As future work, we will model our three scenarios in Simulator “Anylogic” then simulate them with the data of GHT “Loire” in order to determine the level on which every constraint should be taken into account for a given trade-off between reactivity and optimality.

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