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SYSTEMICS FOR THE DESIGN OF A COMPLEX DISTRIBUTION NETWORK WITH UNCERTAINTIES

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ABSTRACT
In the future, hydrogen could be used as a fuel for cars to satisfy objectives of reduction in carbon emissions. To introduce hydrogen on the energy market, a Distribution Network of Hydrogen Energy (DNHE) has to be developed. The DNHE is a complex system composed of several elements (production, liquefaction, transportation, delivery…) in interaction. The challenge for potential energy market actors, like AIR LIQUIDE, is to measure the investments that have to be done in order to develop a distribution infrastructure satisfying cost objectives, environmental constraints and customers' satisfaction in an uncertain framework.
To design distribution networks, the use of optimisation tools is advised. It requires modelling the system. When the system exists, the modelling can be done and validated with comparison to the real system. In the DNHE case, as the system is not developed, the modelling is complex. The originality of this paper is to propose the use of a systemic approach to build an optimisation model of this complex system. We call this modelling method from systemic SCOS'M: Systemics for Complex Organisational Systems' Modelling. We apply the SCOS'M method to the DNHE to identify all the necessary parameters to build a complete and robust optimisation model regarding the objectives of the system.

Keywords: complex system, uncertainties, modelling, design, systemic approach, distribution network, hydrogen energy

1 INTRODUCTION
In this paper, we consider the design of distribution networks. A distribution network is the whole system, composed of commercial establishments and intermediaries by which produces circulate from a producer to a consumer. To design a distribution network, inter-organisational aspects, complex structures and uncertainties linked to the development of the network have to be considered.
In product design, there are several tools, like functional analysis, MERISE or QFD, or standards to guide the design of a product satisfying its own objectives and environmental constraints. For the design of organisational systems, and more precisely for distribution networks, there are no dedicated tools to guide the modelling when the system does not exist.
The design of a new distribution network is required, for instance, to study the feasibility of development of a future product or a future market. In this case, the building of a whole network from nothing, its design, and thus its modelling are complex.
Our purpose in this paper is to propose a method for modelling complex distribution networks. We will support our proposal with a real case study: the Distribution Network of Hydrogen Energy (DNHE).
Indeed, environmental concerns and increasing energy demand involve a radical change in energy scene. To stop, at least slow down, effects of greenhouse gas (GHG) emissions on climate, it is necessary to turn into a carbon free energy system. Moreover, limited resources of fossil fuels impose an energy system based on renewable sources. In this context, several new alternatives appear in energy market. In transport sector, hydrogen, feeding a fuel cell, is an interesting option for vehicles, because it is a GHG free power system. However, technological improvements are needed before hydrogen could be used in personal cars and a dedicated infrastructure has to be built. For these

reasons, energy market actors may be interested in developing devoted hydrogen production and/or distribution infrastructure and network to penetrate this new and promising energy market. The DNHE we consider is the system that allows distributing hydrogen to energy clients, satisfying the constraint of limitation of GHG emissions.

The purpose of our work is ultimately to build a decision-making tool in order to assist the French gas provider AIR LIQUIDE in planning the investments entailed by the development of a DNHE throughout France and Benelux over a fifty-year horizon. To achieve this goal, we need, as preliminary work, to model the DNHE, and then use this model to optimize the development of the system. The major difficulty to model the DNHE is that the system does not exist. A lot of uncertainties apply on the system, the limits of the system are not well defined and the actors of the system are numerous. This report leads us to look for a modelling support method for complex distribution systems.

In chapter 2, we present the difficulties to design complex future distribution networks. We underline the lack for modelling support methods. In chapter 3, we propose to use a systemic approach as a support method to build a model in the design process. In chapter 4, we demonstrate the applicability of the proposed method to the modelling of a DNHE. Chapter 5 underlines the interest of the method and chapter 6 contains our conclusions.

2 DESIGN OF COMPLEX DISTRIBUTION NETWORKS

In our work, we focus on the design of large and complex distribution networks, with numerous uncertainties.

The concept of system was studied by Le Moigne [1] who defines it as "*a structure which, in the environment, equipped with finalities, carries out a design activity and sees its intern structure evolving through time, without losing its structure identity*". A complex system is a system whose behaviour can not be predicted regarding the behaviour of its components because of back loops in the interaction chains and because the response of the system is not the sum of the responses of its subsystems. A distribution network, composed of several subsystems (production, transportation …) is a complex system.

To optimally design a distribution system, one approach is to create a model of the system to make simulations and/or optimisations. These simulations allow choosing the best values for parameters to design the system. The first difficulty for a complex, large and uncertain system is to determine the parameters to get into the model.

In the literature, there are no methods to deal with the design of a complex multi-technological system. The Quality Function Deployment (QFD) method is restricted to mono technology systems. Functional Analysis can be used to determine the functions of the system to be designed, but not to consider the design of the system in a life cycle analysis. This method is not adapted to determine the technical solution in the design of a product.

Three engineering standards are usually admitted: IEEE 1220 [11], EIA 632 [12] and ISO 15288 [13]. Those three standards are not adapted for the same phases of the life cycle. ISO 15288 [13] pretend to emphases on the whole life cycle of a technical system whereas the others concern development or redevelopment phases. ISO 15288 [13] appears as a first level standard, very general. EIA 632 [12] is more precise but in second level and IEEE 1220 [11] very precise but third level (without any continuity between standards).

In the literature, a lot of works deal with validation and verification of models [2][3][4] but no method is proposed to support the modelling step. In ecology, numerous studies have been done to modelling systems. Aumann [5] proposes "*a methodology for developing simulation models of complex systems*". In fact, the proposed methodology consists in a decomposition of the whole system in sub-systems to be able to propose small models of the problem. And then he verifies that the model represents correctly the system. But it is not a method to support the step of building a model

Hernandez-Matias and al. [6] presents a modelling method for manufacturing systems. This method leads to the creation of a database and key performance indicators. It creates a quantitative and qualitative information model of the system. But this method does not consider the objectives of the system regarding its clients and environment. Such method could not be used to take into account all the parameters and the interactions of a complex system.

There are numerous difficulties to model a large and complex future distribution system:

- the limits of the system are not well defined
- all the actors implied are not evident
- all the necessary parameters are not apparent
- the links between each actor and the system are not obvious

The difficulty linked to the modelling of the system reveals a need for modelling methods to warrant any lack of parameters and a sufficient level of description.

3 A SUPPORT METHOD FOR MODELLING: THE SCOS'M METHOD

Contrary to the standard, we propose a generic demarche usable for all phases of the life cycle with precision level choose by the designer at any moment.

In this part, we show how the systemic can be applied as a structured approach for modelling a system. During the design of a new complex system, the objective guides the steps of design, and determines the parameters of this new system. On the basis of this report, we propose a modelling method supported by the own objectives of the system. This method adopts a systemic approach as a support method for building a simulation and/or optimisation model of the system. We will show that this approach leads to the determination of the limits of the system, its framework, and its real objectives. The identification of the parameters needed to describe the system, and consequently, to model it, is then rigorous and complete and leads to the modelling of the system.

The systemic science is the science dedicated to the study of the systems. The concept of system was initiated in the 40's. It was established regarding works of L.v. Bertalanffy, N. Wiener, C. Shannon, Mc Culloch, J.W. Forrester and H.A. Simon. The systemic paradigm appeared in the 50's to complete the previous causal paradigm. It reveals that the knowledge of the system structure is more interesting to predict its behaviour than the detailed knowledge of its initial conditions. Systemics come from the holism theory of L.v. Bertalanffy, the cybernetic theory and the structuralism theory [9]. Four fundamental concepts, useful to understand what a system is, are the interaction (non linear causality), the totality (the whole system is more than the sum of its parts), the organisation (the hierarchical structure guides the proprieties of the system) and the complexity (linked to the organisation of the system, the uncertainties of its environment, the difficulty to identify all the elements).

In American literature, systemics is called systems engineering (SE). Lewkowicz [7] describes SE as a top-down design and development methodology for the engineer. He explains how SE can be used to improve customer satisfaction and profitability. He proposes a common definition of SE like "the process of selecting and synthesizing the application of … knowledge in order to translate system requirements into a system design and … to demonstrate that it can be effectively employed as a coherent whole to achieve some stated goal of purpose." He presents the classical method of SE in four steps: requirements definition, technology assessment, solution synthesis, and performance verification. He concludes that the SE can be used to provide an efficient, cost-effective solution to the managerial and technical challenges but only if the need for a rigorous design methodology is obvious because it is difficult to implement it in enterprises. Its method concerns only physical systems.

The systemic approach proposed by Le Moigne [1], re-appropriated and developed by Perron [8], studies the system as a composition of subsystems in interaction and it is adapted to all the kind of systems, not only products. Systemic approach is a global approach, so, it allows avoiding errors of reductionism often resulting of a traditional analytical approach, which is not adapted for complex system design [9].

The method we propose to model a distribution network comes from the global SCOS' (Systemics for Complex Organisational Systems) method [10] to analyse complex organisational systems. The SCOS' method consists to decompose the system into subsystems. Then, for each subsystem, keeping in mind all the links between them, the methodology exposed with Table 1 is followed.

Table 1. Steps of the SCOS' method

1	To break up the system into phases of its life cycle
2	To clarify the finalities of each customers and the constraints of each surrounding for each phase
3	To express the purposes into deliverables
4	To work out the processes which will produce deliverables
5	To allocate the necessary resources to the processes activation

6	To realize the processes
7	To control the effectiveness of the process / finalities

Our SCOS'M (Systemics for Complex Organisational Systems' Modelling) method is an adaptation, for the modelling of a distribution network, of the SCOS' method. The SCOS'M method presented in Table 2 considers only the four firsts steps of the general SCOS' method.

Table 2. Steps of the SCOS'M method

0	To decompose the system in subsystems
1	To break up the system into phases of its life cycle
2	To clarify the functions accomplished by the system to satisfy environment objectives and constraints for each phase
3	To express the purposes into performance criteria
4	To determine the parameters and variables of the system

In the SCOS'M method, to define the different phases of the life cycle, we decompose the system regarding the three poles proposed by Le Moigne [1]: the Ontological Pole (description of what the system is), the Functional Pole (what the system does), The Genetic Pole (what the system becomes). We consider the teleological aspects (what the finalities of the system are) as a fourth pole like proposed by Perron [8] and Bocquet [10]. Figure 1 is the illustration of the decomposition of an industrial system following those four axes.
Completing each box of this diagram leads to a complete description of the system and to the phases of its life cycle (step 1 of the method). From this complete description of the system, the step 2 consists to determine the functions accomplished by the system. The step 3 corresponds to the identification of the performance criteria. Step 4 consists, from those criteria, to determine the parameters and variables of the system (step 4).

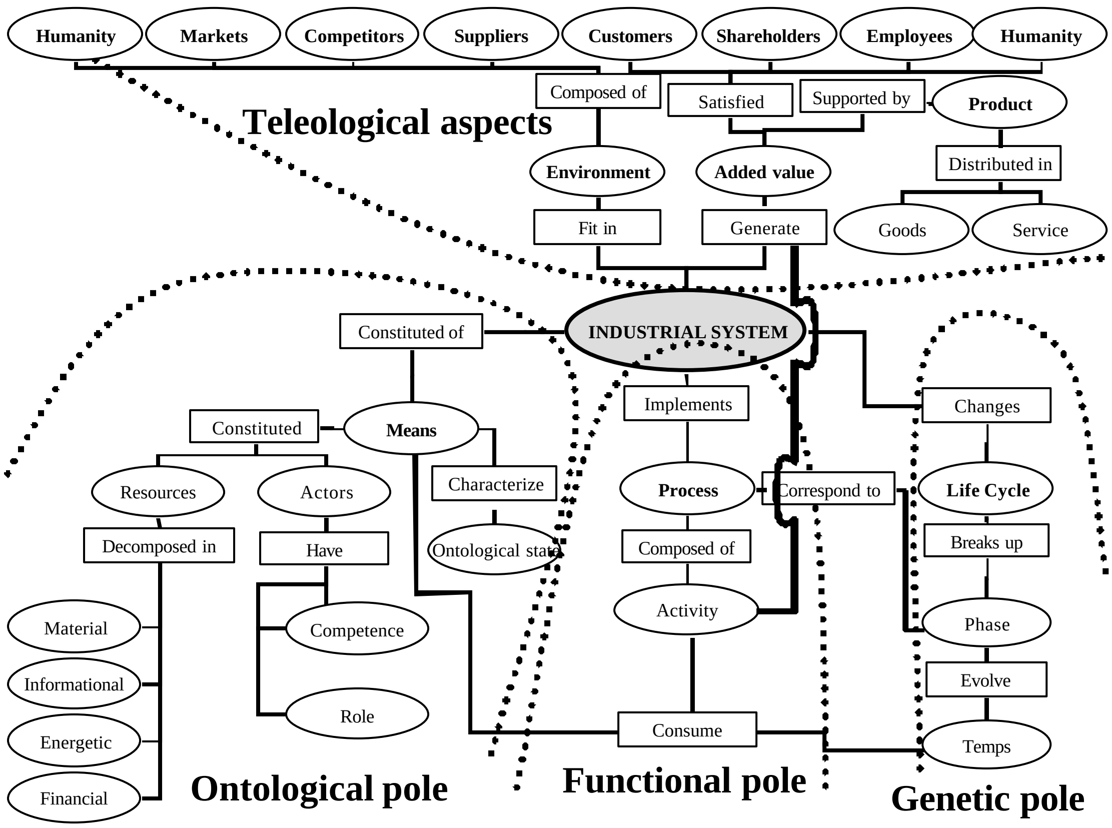

Figure 1. Systemic analysis of an industrial system (extracted from [8])

The SCOS'M method allows determining:

- the pertinent parameters of the complex system to design
- a simulation model which links the complex system parameters

The SCOS'M method is used to identify the variables required and necessary to describe the system, considering its own objectives.
In the following chapter, we apply the SCOS'M method to the DNHE.

4 DESIGN OF A DISTRIBUTION NETWORK OF HYDROGEN ENERGY

The DNHE is composed of several stages from production to final consumption. Indeed, hydrogen (H2) is a gas, not in a natural state on Earth. It must be produced from different raw materials (natural gas, biomass…), transformed (compressed or liquefied), stored, transported and distributed to customers. Hydrogen can be produced from several primary energy sources: by reforming from fossil resources like natural gas and coal, by electrolysis from electricity and water, or by gasification from biomass. Some processes producing CO2 need to be combined with a capture and sequestration unit of CO2 to make the system a free carbon system.
Subsequently, due to its very low volume density, hydrogen needs transformations to be stored and transported. Hydrogen can be compressed from a low pressure, out of production unit, to efficient storage pressures (we talk about Compressed Gaseous Hydrogen – CGH2). Hydrogen can also be liquefied (Liquid Hydrogen – LH2) making it possible to store ten times larger quantities in the same volumes than compressed hydrogen. To transport LH2 requires a liquefaction step and the use of cryogenic storage and trucks. Another way of transporting hydrogen is as medium pressure gas (Gaseous Hydrogen – GH2) in pipelines. Eventually, hydrogen should be distributed to customers. Refuelling stations should permit to fill a tank in a reasonable time at a high pressure or as a liquid. Hydrogen could be delivered to the station in different conditioning: in bulk, as a liquid or a gas, or directly in full tanks.
The characteristics of the DNHE (the system does not exist, a lot of uncertainties apply on the system, the limits of the system are not well defined and the actors of the system are numerous) drive us to make a systemic analysis. It allows to well define the system and its objectives, in order to identify the variables needed to model the DNHE. Consequently, we use the SCOS'M method to build the model of the system.

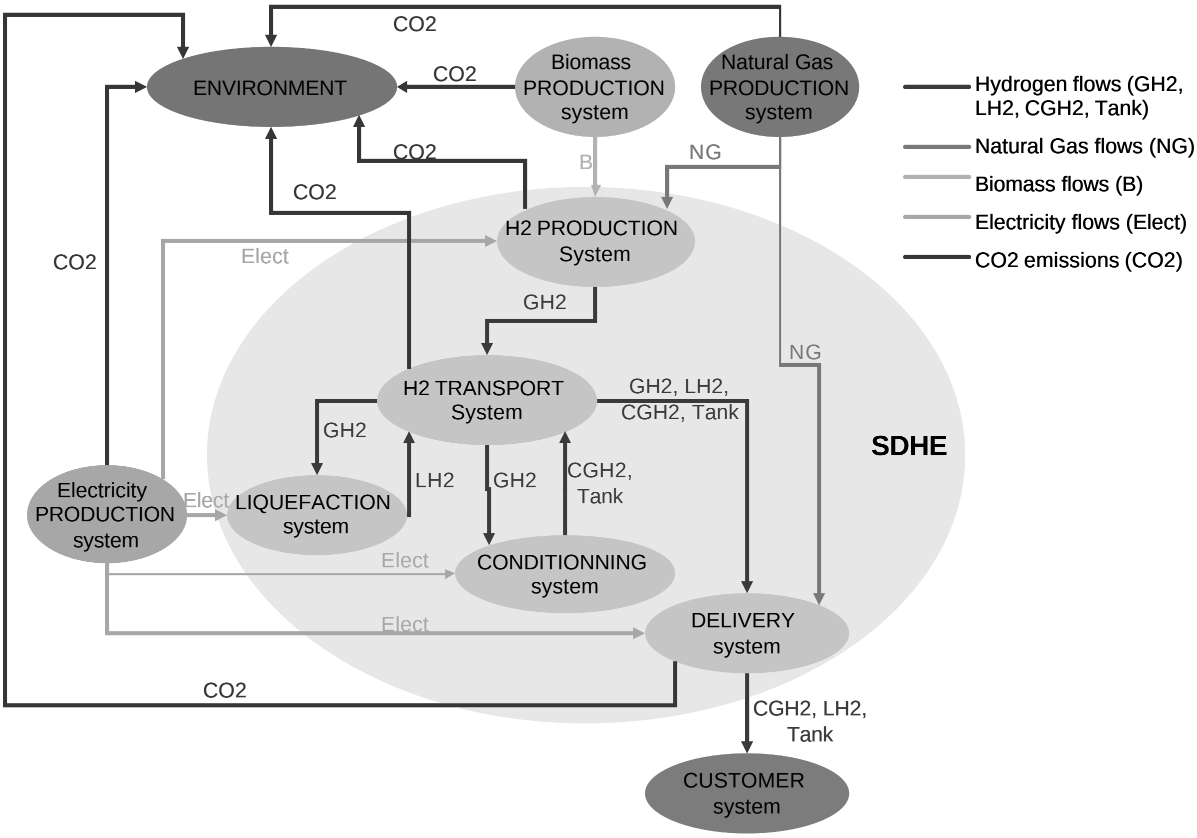

Figure 2. Presentation of the Distribution Network of Hydrogen Energy

The SCOS'M method requires initially to isolate the system, regarding its relations with its surrounding. It obliges to specify the limits of the design field and the system to be conceived. The expression of the phases of the life cycle of the system results "mechanically" in the consideration of its customers and surrounding specific needs. This kind of engineering of the requirements allows a robust expression of needs.

To follow the steps of the approach, we will consider the whole system; decompose it into subsystems regarding the interactions between the pairs of identified subsystems.

The preliminary degree of decomposition of the system into functional sub systems is proposed in Figure 2.

The criteria used to determine if the decomposition was detailed enough is the equilibrium of the material flows between the subsystems. Regarding the material flows, we decided to divide some systems in more subsystems. For example, the hydrogen transport system is separated in three subsystems (cf. Figure 3): the LH2 trucks system (transport liquid hydrogen – LH2 – into cryogenic trucks); the CGH2 trucks system (transport compressed gaseous hydrogen – CGH2 – or full tanks – Tank) into trucks; the Pipeline system (transport gaseous hydrogen – GH2 – into pipelines).

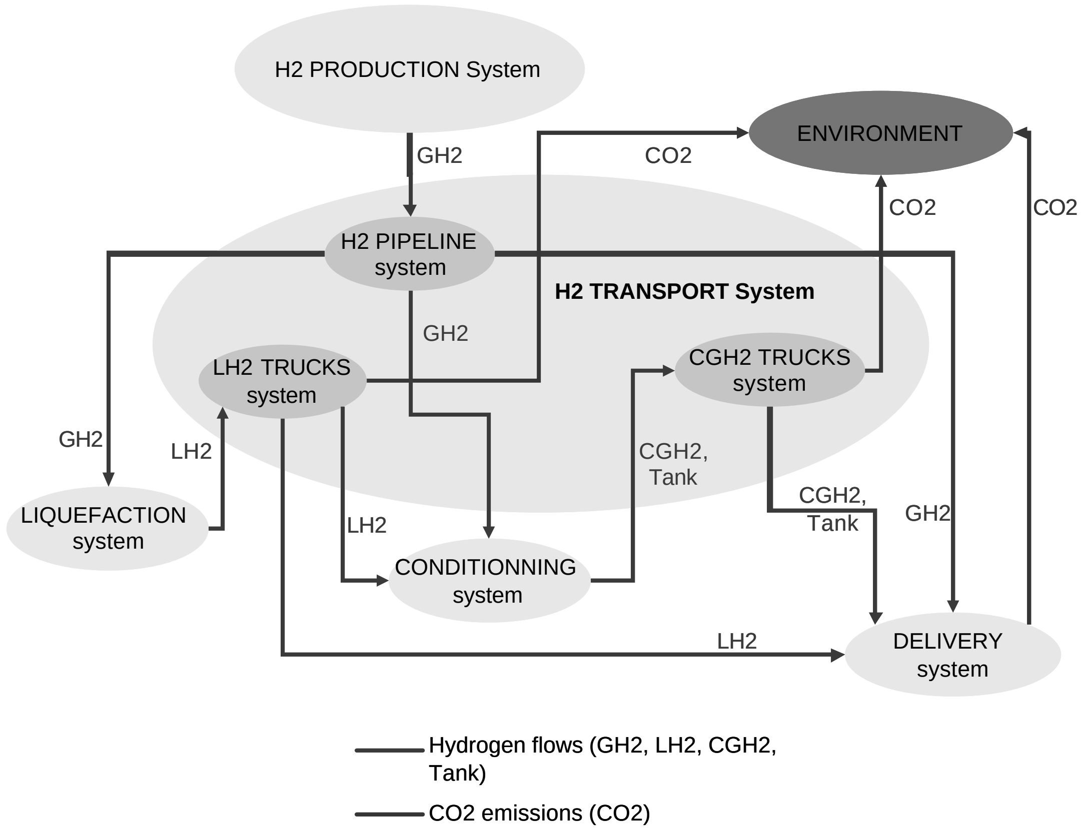

Figure 3. Decomposition of hydrogen transport system

The Figure 3 emphasises the complexity of the DNHE. Going into details for the description of the system underlines the huge number of elements to consider and their interactions.
The system description method presented with Figure 1 was applied to define the teleological, ontological and genetic aspects of the DNHE. They are partially presented in Table 3, Table 4 and Table 5.

Table 3. Part of the description of the teleological aspects of DNHE

Teleological aspects	The DNHE fits in an **environment** composed of:	
	Markets	- energy in transport - heating for residential - …
	Competitors	- current fuel suppliers - current hydrogen suppliers - …
	...	
	The DNHE generates **added value** supported by:	
	Goods	- hydrogen - at fixed pressure dependant of the application - …
	Services	- supply fuel to motorists - supply energy to stationary clients - …
	The DNHE generates **added value** satisfying:	

	Customers	- stationary applications: - availability - cost - flow	- motorists : - good repartition on area - availability - cost - velocity for filling
	Stockholders	- profit	
	Employees	- hardness - security - …	

Table 4. Part of the description of the ontological aspects of DNHE

Ontological aspects	The DNHE is constituted of **means** :		
	Resources	- Material : - H2 production system - transport system - … -Informational : - demand repartition - regulations - …	-Energetic : - electricity - … -Financials : - cost of each subsystem - interaction costs of subsystems
	Actors	- suppliers - system owner - employees - …	

Table 5. Part of the description of the genetic aspects of DNHE

Genetic aspects	The DNHE changes during its life cycle decomposed in :		
	Phases	- technologies study - implantation study - implantation	- exploitation - maintenance - dismantling

The creation of those tables gives:

- a complete description of the system
- the phases of its life cycle (step 1 of the method)

From this complete description of the DNHE, we use the functional analysis to determine the functions accomplished by the system (corresponding to step 2 of the method). Then, we identify the performance criteria (step 3): constraints or objectives, corresponding to each function the system should fulfil. We show a part of those functions that link the DNHE to the components of its environment (constraint functions: Fc; and principal functions: Fp) in Table 6.

Table 6. List of functions and criteria of the DNHE

	N°	Function to be fulfilled by the system to satisfy actors	Performance criterion: **constraint or objective**
Implantation	Fc1	Not exceed capital budgets allocated	Capital cost < capital budget
	Fc5	Use mature technologies	Maturity of technologies
Exploitation / Maintenance	Fp1	Not be too expensive for stockholders regarding CO2 taxes	Min (Ton of CO2 × tax)
	Fp2	Provide, with other new energies, a solution to limitations of stocks of fossil fuel	Min (Consumption of fossil fuel)
	Fp5	Create jobs	Max(Number of created jobs)
	Fp6	Generate profit	Max(Incomes/ Cost)

	Fc7	Not saturate the road traffic	Min (Number of trucks)

This description revealed about thirty functions. Next step is, from those criteria, to identify the parameters and variables of the system (step 4).
The same approach was made for all subsystems, and revealed the following list of variables and parameters presented in Table 7 and Table 8.

Table 7. List of the variables of the model

Type of variable	Element concerned	Type of variable	Element concerned
Number of elements to build	- Production units - Liquefaction units - Refuelling stations - …	Length of pipeline to build	- Distribution pipeline - Transportation pipeline
Flows passing through the element	- Production units - Liquefaction units - Refuelling stations - …	Distance	- Average distance between stations - …
Number of elements to buy	- Cryogenic trucks - Gas trucks		

Table 8. List of the parameters of the model

Type of parameter	Element concerned	Type of parameter	Element concerned
Price	- Primary energy sources - …	Employment	- Production units - Liquefaction units - Refuelling stations
Capital cost	- Production units - Liquefaction units - Refuelling stations - Pipeline - Trucks - …	Capacity	- Production units - Liquefaction units - Refuelling stations - Pipeline - …
Cost of exploitation	- Production units - Liquefaction units - Refuelling stations - Pipeline - …	Cost of dismantling	- Production units - Liquefaction units - Refuelling stations - Pipeline - …
Maturity of technology	- All	Degradations (sound)	- All
Energy consumption	- Production units - Liquefaction units - Refuelling stations - …		

The application of step 4 of the SCOS'M method revealed a hundred variables and parameters necessary to model the system.
To come back to the general SCOS' method, we can consider that step 5 could correspond to an optimisation step of the model built with the identified variables. Step 6 and 7 correspond to its validation.
To run the SCOS'M method on the DNHE, we have studied the actual distribution network for hydrogen as an industrial gas. Thus we have interviewed experts and managers and we have visited industrial sites. Then, we have studied similar products distribution networks, like butane or propane. From those analyses, we have characterized elements that should be present in the DNHE.

5 INTEREST OF THE SCOS'M METHOD

The interests of the SCOS'M method are numerous. Firstly, the system we want to design and model is complex and a holistic analyse of it allows to be more rigorous in the description. Then, the description is not obvious because the system does not exist. The advantage of the SCOS'M method is that it starts from the expression of the requirements of the clients to design the system. It is a systematic and guided method. Thus, those points reveal that the SCOS'M method is good for a complex and uncertain system.

Furthermore, another interest is the characteristics of flexibility and evolution of the created model. In the following chapter, we underline this possibility of evolution of the model. Then, we propose elements of validation for the method.

5.1 Flexibility and capability of evolution of the model

The parameters identified with the SCOS'M method were used to build a simulation tool. The first objective of the tool was to simulate the costs of the system. Next, we wanted to consider the global CO2 emissions of the system. With the identified parameters, it was then easy to reintroduce the calculation of the global CO2 emissions. All the parameters required to calculate it were in the model. Because we have considered all the possible systems interactions, the developed model is flexible.

5.2 Validation of the approach

The validation of the method like proposed in the literature [5] with comparison of the model results and the real system response, is not adapted when the system does not exist.

In this case, the validation is done with experts. For the DNHE, we submitted results to AIR LIQUIDE experts who have validated the model. They have validated the method and its possibility of adaptation to the analysts' requirements. The model obtained with application of the SCOS'M method has been implemented in a software.

The model was used to build simulation software. This tool allows running a lot of simulations different sets of parameters from which we have built a function representing the total costs of the system depending on only ten important variables we choose to consider. The simulation results have been validated. An example of some simulation results is shown with Figure 4. The three networks simulated and represented on Figure 4 contain ten reforming units and neither conditioning nor liquefaction units. The transport of hydrogen is done entirely with pipelines.

The cost function elaborated from those simulations will then be used to optimise the system. Those results are under working and will be published in a next paper.

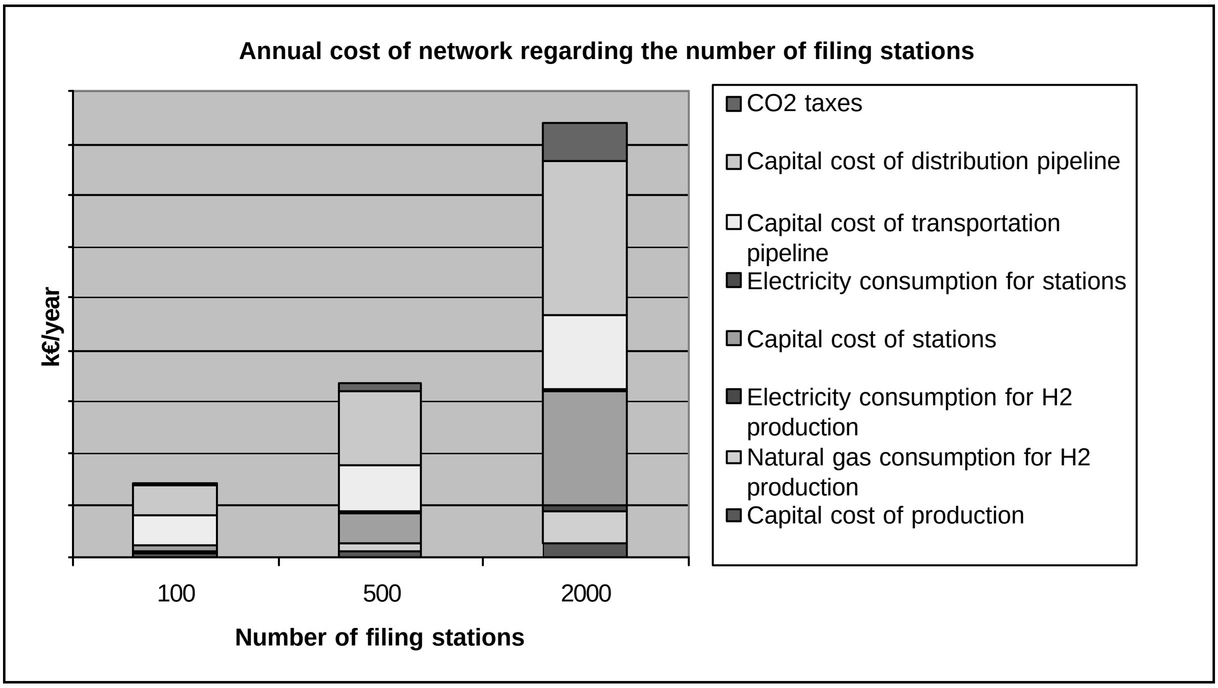

Figure 4. Cost of networks regarding the number of filing stations

6 DISCUSSION AND CONCLUSION

In this paper we have proposed the SCOS'M (Systemics for Complex Organisational Systems' Modelling) method to model the Distribution Network of Hydrogen Energy. We have presented results of the preliminary steps of our work consisting in building a decision support tool for AIR LIQUIDE to make investment decisions about its future hydrogen distribution network. Consequently, the method is efficient to model a complex system in a prospective context. In the DNHE case, we were facing a feasibility study. In such a case, a systemic approach like the SCOS'M method appears to be the best way to make a complete and rigorous description of the problem. But, another interest of the method is that it can accelerate the design process. Indeed, without any method, the approach would have been to make propositions of model, to submit them to experts and to re-design the model with their comments. This validation and correction process is quite long and not necessarily exhaustive in the description.

The SCOS'M method appears as a good modelling support method for the design of such complex and uncertain distribution network, because it allows to have a complete and robust model and requires less time than a validation and correction process.

To conclude, with the results obtained on a specific case, the generalisation of the method to any other distribution network seems to be possible.

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