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RISK ANALYSIS OF COMPLEX HYDROGEN INFRASTRUCTURES

Markert, F.[1], Marangon, A.[2], Carcassi, M. [2], and Duijm, N.J.[1]
[1] Institute Management Engineering, Technical University of Denmark, Produktionstorvet 424, 2800, Kongens Lyngby, Denmark, fram@dtu.dk
[2] Industrial and Civil Department, University of Pisa, , L. Lazzarino n.2, 56126, Pisa, Italy.
a.marangon@ing.unipi.it

ABSTRACT

Developing a future sustainable refuelling station network is the next important step to establish hydrogen as a fuel for vehicles and related services. Such stations will most likely be integrated in existing refuelling stations and result in multi-fuel storages with a variety of fuels being delivered, stored and distributed, as e.g. biomass based methane, ethanol, gasoline, diesel as well as the traditional crude oil based products. Hydrogen is also in play as intermediate energy storage to secure the power supply based on large shares of fluctuating energy sources and as an intermediate to improve the quality of biomass based fuels. Therefore, hydrogen supply and distribution chains will likely not only serve to fulfil the demands of refuelling, but may also be important for the wider electrical power and fuel industries. Based on an integrated hydrogen supply and distribution network, the application of the method of “Functional modelling” is discussed in this paper to show the complexity of the coupling between power storage for electricity supply and supplying hydrogen for transportation. It will be shown how a “Functional model” can be applied for comprehensive data storage for various assessment methodologies, and how functional models could support coherent risk and sustainability (Risk Assessment, Life Cycle Assessment /Life Cycle Costing) assessments, in order to find optimal solutions for the development of the infrastructure on a regional or national level.

1.0 INTRODUCTION

Developing a future hydrogen refuelling station (HRS) network is the next important step to establish hydrogen as a fuel for vehicles and related services. Such stations will most likely be integrated in existing refuelling stations and result in multi-fuel storages with a variety of fuels being delivered, stored and distributed, as e.g. biomass based methane, ethanol, gasoline, diesel as well as the traditional crude oil based products. Hydrogen is also in play as intermediate energy storage to secure the power supply based on large shares of fluctuating energy sources and as an intermediate to improve the quality of biomass based fuels. Therefore, hydrogen supply and distribution chains will likely not only serve to fulfil the demands of refuelling, but may also be important for the wider electrical and fuel industries.

This complicates the operation and control of these multifunctional hydrogen supply and distribution networks. This complexity also puts higher demands on the decision-making process addressing the sustainability and safety of these systems. The challenge for risk analysts is to treat many threads in a dynamical system. The reason is that most tools to ensure safety are designed to deal with individual plants and their components, e.g. fault tree analysis FTA & event tree analysis ETA. The needed fault trees and event trees quickly grow complex, because of the many scenarios to be analysed for their consequences. Therefore, it is demanding to provide risk informed decision support analysis even for rather simple cases as a HRS. From a systemic perspective, though, it is essential to take a holistic approach, as system safety is more than just the reliability of its single components.

A challenge for making strategic decisions on the optimal methods and processes is to deal with and to compare infrastructures taking into account networks of refuelling stations including their supply chains.

The problem is to find methods and solutions based on a risk informed approach that are able to provide useful criteria to support the strategic choices. How could a solution be structured to better cope with the above mentioned challenges and the uncertainties involved? How can one ensure that the various studies that feed into strategic decisions, such as risk assessment, environmental assessment and economic assessment actually deal with exactly the same system? How to compare and decide on different product types in a consistent way? These issues are very complex and, therefore, these are not to be solved in one paper, as they need a broad discussion and further development of tools. Thus, the intention of this paper is to raise awareness about such problems and to start a discussion on possible solutions.

Based on an integrated hydrogen supply and distribution network, the application of the method of "Functional modelling" is discussed to show the complexity of the coupling of functions in a complex hydrogen supply and distribution network, where interferences and strong connections can be found between power storage for electricity supply and supplying hydrogen for transportation. It will be shown how a "Functional model" can be applied for comprehensive data storage for various assessment methodologies, and how functional models could support coherent risk and sustainability (Risk Analysis, Life Cycle Assessment /Life Cycle Costing) assessments, in order to find optimal solutions for the development of the infrastructure on a regional or national level.

2.0 THE SUPPLY CHAIN

Hydrogen is not an energy source in itself and has to be produced from e.g. natural gas or electrical power using steam reforming and water electrolysis, respectively, as indicated in *Figure 1*. The supply chain needs to have storages to store hydrogen for later use, such as small and large scale pressurized storage and / or cryogenic storages. Hydrogen is to be transported using pipelines, trucks or ships between the storage facilities and to the hydrogen refueling stations (HRS) or to industrial / domestic applications.

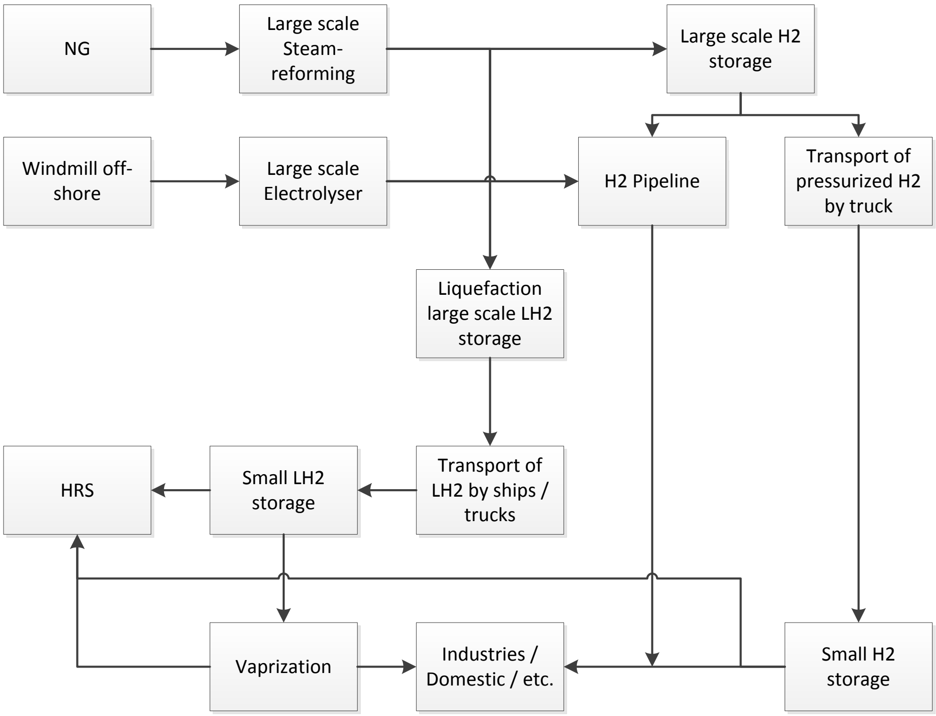

Figure 1. Hydrogen supply and distribution chain

3.0 METHODOLOGY

3.1 Functional analysis

The assessment of infrastructures requires high level hazard identification methods to be practical and effective. Therefore, the method of “Functional modelling” as described by Rasmussen & Whetton [1] is chosen and briefly described here. The methodology is based on the view that an infrastructure is to be seen as a socio-technical system. In order to identify hazards as early as possible during planning and design of the future hydrogen infrastructure a high level identification of hazards is a valuable first step. Methods like FMEA and HazOp are less suited for such concept hazard identification, because they are designed to deal with detailed designs of components and hazards closely related to the technical hardware. Also as pointed out by Rasmussen & Whetton these methods only to a lesser degree account for hazards related to interaction between the different equipment, operator interactions, software, organisational structure and management factors already on a plant level. These interactions are becoming even more pronounced for an infrastructure like a fully integrated hydrogen supply and distribution network.

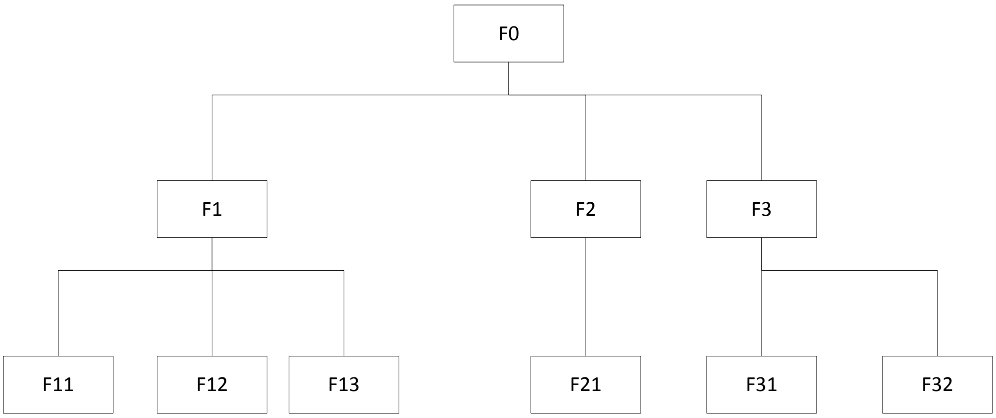

Figure 2. Generic functional breakdown

In Figure 2, the generic framework to apply the functional modelling is shown. The idea is that a set of functions are needed to establish e.g. the hydrogen supply chain made of hardware, software, operations, work organisation and other aspects related to the infrastructure. Each function Fx is seen as an object that fulfils an “Intent” or goal. The “Intent” is associated with “Methods” and “Constraints” that allow to realize or limiting, respectively, the “Intent” itself. The Methods and Constraints themselves can be seen as objects which can be further decomposed into a hierarchy of other lower level Intents.

The starting point F0 in our context is the whole hydrogen supply chain. The first breakdown to level F1..n will be the Intents that make the supply chain work and deliver safely. The next levels F11..nn further decomposes the Intents from the above level into increasingly more detailed elements. The functional breakdown continues until the system’s hazardous areas may be identified with reasonable precision using (high level) hazard identification methods, as described below. Thus, comprehensive hazard identification at design stage is possible using the principles of functional modelling. The processes, inputs, outputs and methods are described, usually graphically, and this graphical model is used to analyse the consequences of deviations in each of the elements in the model. The functional model is hierarchal, which allows analysis to start at top level, and detailed analysis for those elements or process steps that require further attention.

Therefore, the main objective of the functional modelling is to identify at each level the parts where further analysis is required. By that the functional decomposition need to ensure that all relevant activities are incorporated like the various processing, storage and transport steps, the established safety functions, the emergency systems, the controlling software and others. If necessary the decomposing can be continued into very detailed items which then can be analysed through the application of low level hazard identification methods, as e.g. FMEA and HazOp.

Summarizing, the analyst will go through the hydrogen supply chain looking for each level F by asking the question: How is the “intent” performed by what “methods” and with which “constraints”? Also inputs and outputs of the intent should be well identified (Ref. Figure 3 and Table 1).

The functional model uses the SADT (Structured Analysis and Design Technique), also known as IDEF0 (or one of the other IDEF dialects) as included in Microsoft Visio®. The SADT uses an “ICOM” function block, where ICOM normally stands for Input-Control-Output-Method. In our hazard modelling we prefer to interpret the Control as a “Constraint” (the control function can be included in the Method, see Figure 9.). A typical example of a high level constraint would be: “not endangering human life and the environment”

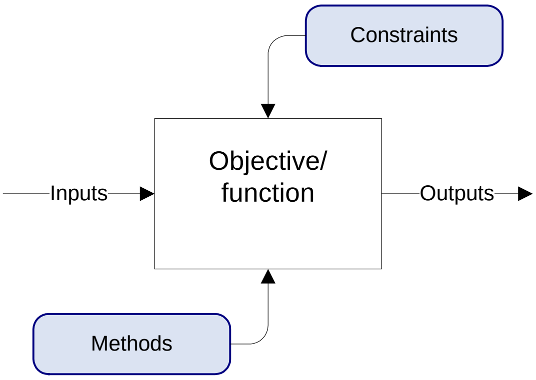

Figure 3 Functional modelling for hazard identification

This function block can be interpreted as:

Do <Objective> by <Methods> respecting <Constraints>

Or:

Produce <Outputs> from <Inputs> by <Methods> respecting <Constraints>

Hierarchy is introduced by expanding each Method as a Function (a child function of the function it contributes to).

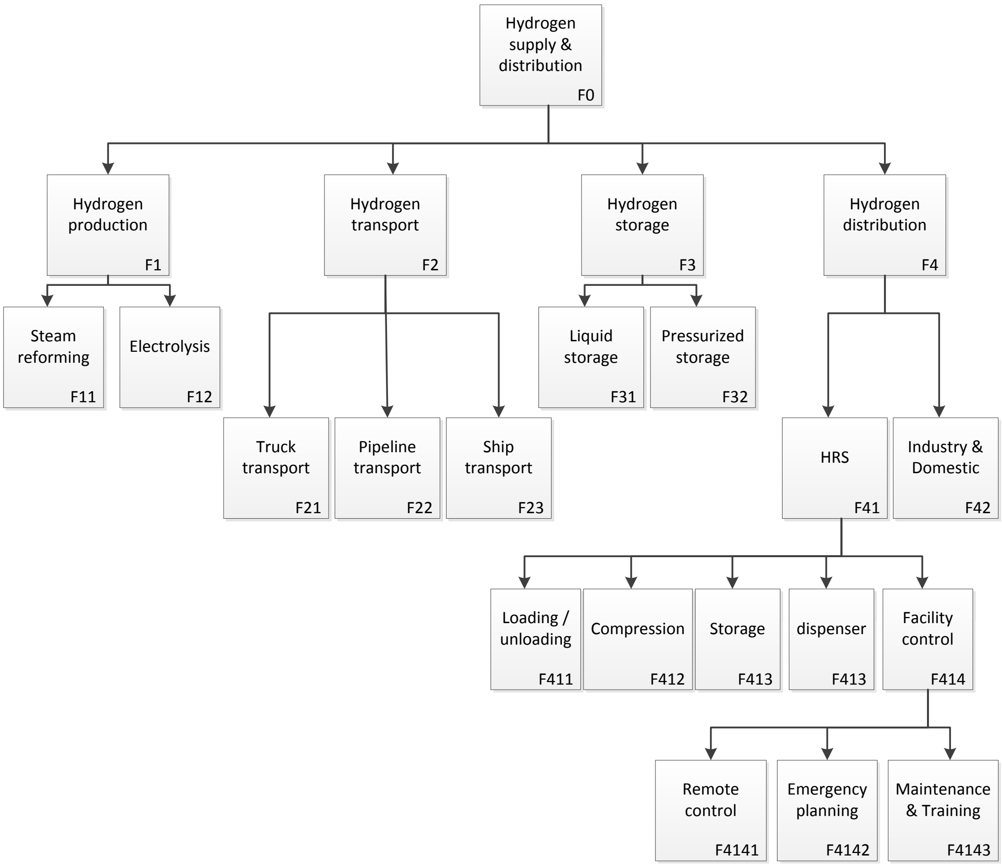

Figure 4 Example of a functional break down of the hydrogen supply and distribution chain

Table 1 Highlight of the interrelation of some functional level. [2]

Code	**Inputs**	**Intent**	by	**Method**	with	**Constraints**	**Outputs**
F12	Electrical power Water Etc.	Hydrogen production		Electrolyser		Max. pressure Availability of cheap power sources Hydrogen purity Etc.	Hydrogen Oxygen Etc.
F21	Hydrogen gas Engine fuel Etc.	Hydrogen transport		Truck		Max. pressure route planning ADR regulation Etc.	Hydrogen gas Engine pollutants Etc.
F3	Hydrogen gas energy Etc.	Hydrogen storage at large amounts		Cryogenic storage Pressurized storage		Max. pressure Temperature control Evaporation control	Hydrogen gas / liquid Engine pollutants Etc.
F4141	Data Power; Etc.	(HRS) remote control signals		Internet/ software HRS safety functions Surveillance: Detection & Alarm →Decision→Action Communication Training		On-line uninterrupted power supply, knowledge on specific HRS intercultural understanding Etc.	Control of HRS

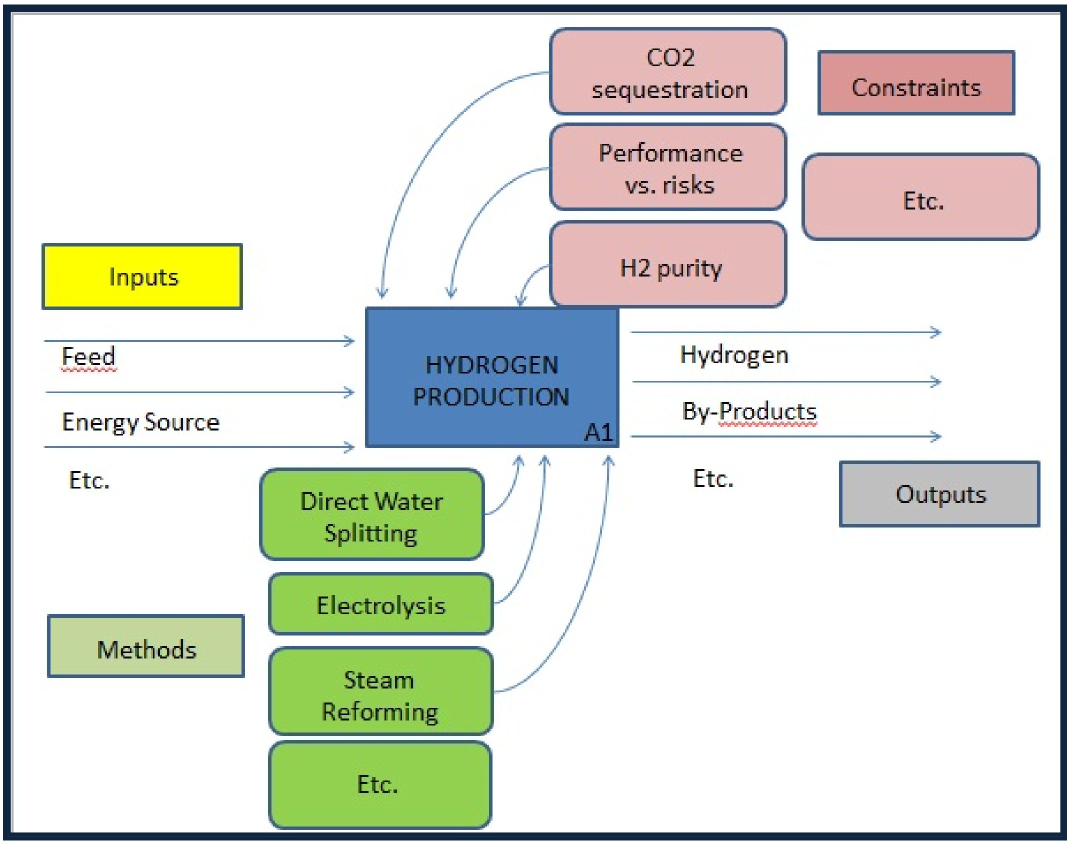

Figure 5. Preliminary functional model for hydrogen production

Now hazard identification can be applied by systematically considering the consequences of deviations in Inputs, Constraints, Outputs and Methods. For this, traditional hazard identification methods can be used such as Checklists or what-if questions. In the following some potential methods to analyse in depth all the block of the functional breakdown are presented.

4.0 HAZARD IDENTIFICATION METHODS

In the literature many other hazard identification methods are described, as e.g. PIRT, FMEA, HAZOP, Event Tree, Fault Tree, Safety Barrier Diagrams, DES, GIS and many other well accepted methods. In the following we will give examples for some of these methods and how they with benefit could be applicable in the framework of functional modelling.

HAZOP

As discussed above HazOp is a method that can be used when the functional breakdown is sufficiently detailed. The method is applied very successfully in process systems regarding the flow of a material through the system. By that the consequences caused by deviations in the systems are systematically recorded. The drawback is the huge demand of resources (persons, time) and the complexity of the outcome, which is not fulfilling the requirements behind the functional modelling philosophy. Nevertheless, HazOp is a top-down technique that would fit nicely to the hierarchical structure of a functional decomposition. The elegance of HazOp is that it allows combining the relevant characteristics with guidewords (such as *No, More, Less, Reverse, Late, Before…*) in order to generate possible deviations. Solving hazards can be assigned to methods in the functional model, or by choosing the right implementation to fulfil an intent. Therefore, with some adoptions to the HazOp method, it should be possible to apply the method in the context of the higher levels of functional modelling. The properties of the outputs, inputs, constraints and methods could be similar combined with modified guide words (e.g. guideword “no” + “method x” means method X is not performed). This is a novel idea of performing HAZID by means of functional modelling, which is more rigorous compared to Whetton’s Concept Hazard Analysis being presented in the following, which originally was suggested to be applied with the functional model, but does not exploit the functional decomposition optimally.

CONCEPT HAZARD ANALYSIS

As originally suggested by Wells et al [2] and adapted by Rasmussen & Whetton [1] the functional breakdown may be analysed for hazardous areas using the method “Concept Hazard Analysis” (CHA). The method may be used in early stages of planning and design of a supply chain and need only block diagrams or preliminary process flow diagrams as input. The method’s aim is to identify the main hazards. Based on the achieved functional break down of our system for each area keywords are applied that the group of analysts have agreed on. The keywords are addressing generic issues, as shown in Table 2. Therefore, the team performing CHA has to adopt a set of relevant specific keywords for the given analysis.

Table 2 List of generic keywords used in “Concept Hazard Analysis” as suggested by [2]

Flammables	*Ignition* *Fire* *Explosion / detonation*	**Mechanical hazards**	*Structural hazards* *Collapse, drop*
Chemicals	*Toxicity* *Corrosion* *Off-specification*	**Mode of operation**	*Start-up / Shutdown* *Maintenance* *Abnormal* *Emergency*
Pollutants	*Emissions* *Effluents* *Ventilation*	**Release of material**	*Release on rupture* *Release by discharge* *Fugitive emissions* *Periodic emissions* *Handling / Entry*
Health hazards	*Chemical contact* *Noise* *Illumination*	**Loss of services**	*Electricity* *Water* *Other services*
Electrical/radiation hazards	*Electrical* *Radiation* *Laser*	**External threats**	*Accidental impact; Drop/fall; Act of God* *Extreme weather* *External interferences* *Loosening / Vibration* *Sabotage / Theft* *External energetic event* *External toxic event* *External contamination* *Corrosion /erosion*
Thermodynamic hazards	*Over- / under pressure* *over- / under-temperature*		

Table 3 Analysis of the found intents (I), methods (M) and constraints (C) using selected keywords from CHA

Function			**Concept Hazard Analysis**				
Ref	*T*	*Description*	*Keyword*	*Main variance*	*Consequences*	*Mitigation*	*Notes*
F12	M	Water electrolysis	Chemicals: Corrosion	Release → Fire	Heat radiation on equipment	ATEX	
F21	M	Truck transport (pressurized)	Thermodynamic hazards: over temperature	Weakening of truck tank walls under filling	Tank rupture	Slow filling, pre-cooling	Depends on storage type
F3	I	Hydrogen storage	External: Accidental impact due to obstacle collision	Structural damage: →leakage →insulation	Release of hydrogen / overpressure in cryogenic system	Fences authorization to enter	
F4141	C	On-line with data connection	Mode of operation: Abnormal	Off-line → Loss of control of HRS	Possible escalation of minor events	High SIL level local operation	HRS shuts automatically down on loss of data connection

Application of geographical information systems GIS

An important issue, when analyzing hydrogen supply and distribution networks, is the knowledge about the specific geographical positions of the hazardous areas to evaluate for social risk criteria. This is closely related to decisions on additional preventive and mitigating measures to ensure the acceptance criteria of a given installation. It is important to know about the population density, the environmental vulnerability and the location of hospitals, emergency service etc. along the networks. For this GIS is a very efficient and valuable tool (see e.g. [3] as it allows to superimpose thematic maps and to analyse for e.g. the population density for any geographical position). It is straight forward to model the hydrogen supply and distribution networks with a GIS environment using established geographical maps and CAD drawings from the planning state of the networks. As the functional model regards the intents as objects, it is possible to attach graphical object(s) with an intent and by that preserve the geographical position together with the attributes listed in the table form of the results of the functional model and the results of hazard identification tables.

For a quantitative risk assessment data on the system state (amounts, pressures, temperature, etc.) could as well be attached to the graphical objects supporting consequence assessments, while necessary weather, population densities and other data could be provided by respective thematic maps.

Life cycle assessment and Life cycle costing

Establishing sustainable hydrogen supply and distribution networks it is not sufficient only to evaluate the safety aspects that provide the social acceptance of the emerging technology. Decision support has also to be provided concerning the environmental aspects and the economic aspects of sustainability using the methods of Life cycle assessment (LCA) and Life cycle costing (LCC). The LCA method has been standardized by ISO standards [4]. The steps to perform the assessment is starting with a goal and scope definition and is defining the fuel unit (called functional unit) that is followed through the different stages of the life cycle of the fuel, as shown in Figure 7. This could here be defined as e.g. a unit of 5kg hydrogen (i.a. a tank fill). The second step is to establish a comprehensive inventory for all the materials going into and out of the stages and energies used. This is then followed by an impact assessment to predict environmental and human effects of the effluents and the resources used. For each step an interpretation of the results is done.

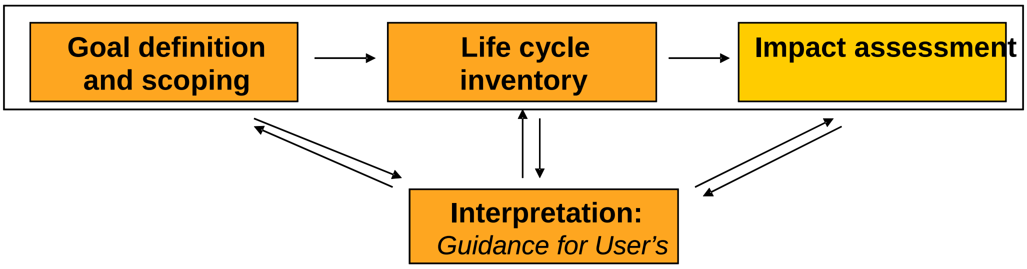

Figure 6 Steps in Life cycle assessment according to ISO standard [4]

Similar the LCC method [5]is regarding the cost flow of the stages and is directly following the same model as the LCA. This makes the results excellent comparable. It is also seen the similarity between the functional modelling and the LCA/LCC approach, as the functional block is also looking for the inputs and outputs and the functions on level F1 to F4 are directly comparable to the stages 1 to 4 of the LCA/LCC. Therefore, the functional model output tables may be widened to include the essential approbriate aggregated data of the Life cycle inventory.

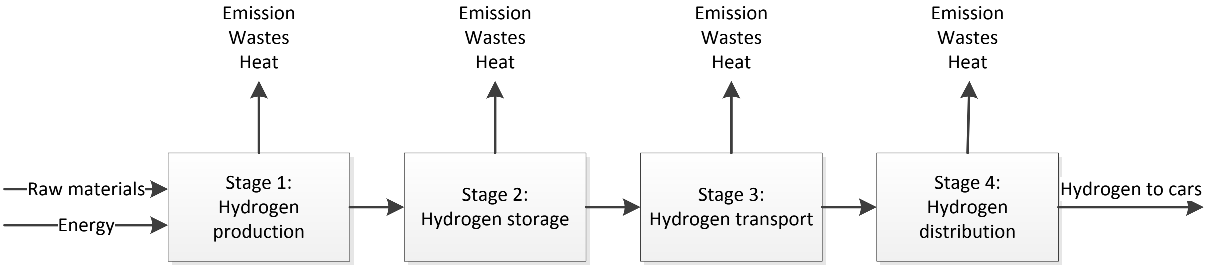

Figure 7 Stages of a LCA/LCC assessment for a fuelling system

5.0 DISCUSSION AND CONCLUSION

The risk assessment of a complete supply chain is analyzed using the functional modelling approach and the conceptual hazard analysis methodology. The high level risk analysis enables the efficient risk assessment and help to restrict the assessment to the hazardous parts of concern. The functional modelling allows the modelling of new designed technologies and may be more and more detailed as new information and alternative technologies are implemented. At a certain level there is a transition where a low level assessment is appropriate, which is easily handled by the approach and the application of FMEA and HazOp is also supported.

The results of the functional break down may be presenetd as tables or as a functional graph. The latter may be also implemented as a GIS database, where the geographical information is preserved along with the detailed technical information necessary. Using GIS the analysis can be easily extended using thematical maps and by that the identification of vulernable objects is facilitated. This enables a generic risk assessment as modules of hydrogen components that easily are placed in the specific environment that in the end has to be assessed.

For a holistic decision support other sustainability aspects as the environment and the economical ones are needed and they should be based on the same detailed model to ensure consistent modelling of systems. It is shown that the basic model used for the functional breakdown can be similar to the stages of the LCA/LCC and by that the functional model database may be used as the comprehensive database to collect relevant input, output, methods, constraints, graphical data and inventory data to ensure a single place storage and maintenance of the needed data and assumptions.

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